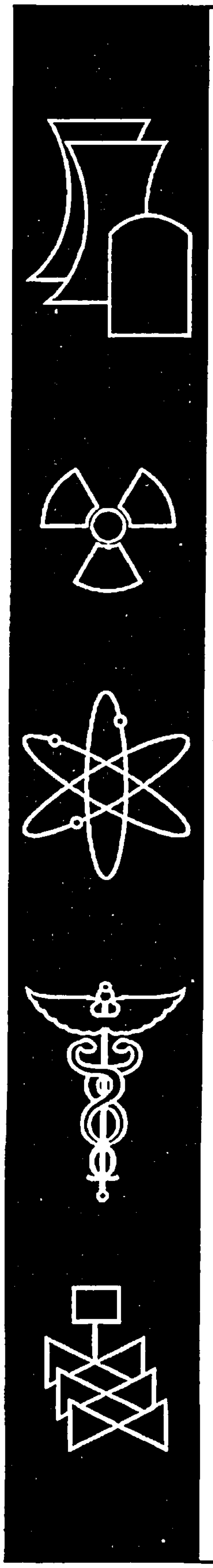
NUREG/CR-5698



# Comparing Monitoring Strategies at the Maricopa Environmental Monitoring Site, Arizona

**University of Arizona**

**U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001**

# AVAILABILITY NOTICE

## Availability of Reference Materials Cited in NRC Publications

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy,* of the *Code of Federal Regulations,* may be purchased from one of the following sources:

1. The Superintendent of Documents
   U.S. Government Printing Office
   P.O. Box 37082
   Washington, DC 20402–9328
   <http://www.access.gpo.gov/su_docs>
   202–512–1800

2. The National Technical Information Service
   Springfield, VA 22161–0002
   <http://www.ntis.gov/ordernow>
   703–487–4650

The NUREG series comprises (1) brochures (NUREG/BR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) technical and administrative reports and books [(NUREG-XXXX) or (NUREG/CR-XXXX)], and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Office Directors' decisions under Section 2.206 of NRC's regulations (NUREG-XXXX).

A single copy of each NRC draft report is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001
E-mail: <DISTRIBUTION@nrc.gov>
Facsimile: 301–415–2289

A portion of NRC regulatory and technical information is available at NRC's World Wide Web site:

<http://www.nrc.gov>

All NRC documents released to the public are available for inspection or copying for a fee, in paper, microfiche, or, in some cases, diskette, from the Public Document Room (PDR):

NRC Public Document Room
2120 L Street, N.W., Lower Level
Washington, DC 20555–0001
<http://www.nrc.gov/NRC/PDR/pdr1.htm>
1–800–397–4209 or locally 202–634–3273

Microfiche of most NRC documents made publicly available since January 1981 may be found in the Local Public Document Rooms (LPDRs) located in the vicinity of nuclear power plants. The locations of the LPDRs may be obtained from the PDR (see previous paragraph) or through:

<http://www.nrc.gov/NRC/NUREGS/SR1350/V9/lpdr/html>

Publicly released documents include, to name a few, NUREG-series reports; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigation reports; licensee event reports; and Commission papers and their attachments.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, Two White Flint North, 11545 Rockville Pike, Rockville, MD 20852–2738. These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
<http://www.ansi.org>
212–642–4900

---

NUREG/CR-5698

# Comparing Monitoring Strategies at the Maricopa Environmental Monitoring Site, Arizona

Manuscript Completed: June 1999
Date Published: July 1999

Prepared by
M. H. Young*
A. W. Warrick, P. J. Wierenga, L. L. Hofmann, S. A. Musil**

**Department of Soil, Water and Environmental Science
University of Arizona
Tucson, AZ 85721

T. J. Nicholson, NRC Project Manager

**Prepared for**
**Division of Risk Analysis and Applications**
**Office of Nuclear Regulatory Research**
**U.S. Nuclear Regulatory Commission**
**Washington, DC 20555-0001**
**NRC Job Code W6151**

---

*Currently at School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0512

# ABSTRACT

The purpose of this document is to discuss the alternative monitoring strategies used during field experiments at the Maricopa Environmental Monitoring site, Maricopa, AZ. The strategies used at Maricopa were selected so that they could potentially be incorporated into monitoring programs at Low Level Waste disposal facilities. Although the evaluation of the strategies was mostly qualitative in nature, they were supported by data collected during two, field-scale infiltration experiments. The results of the field experiments with respect to water movement and tracer migration were presented in a companion NUREG report (NUREG/CR-5694). The emphasis was on monitoring in the vadose zone.

This document describes and compares four monitoring strategies that were implemented at the Maricopa site. They were designated as Monitoring Trenches, Monitoring Islands, Borehole Monitoring, and Geophysical Monitoring. The strengths and weaknesses of each strategy were described with respect to installation, maintenance and replacement of monitoring systems and instruments. Monitoring Trenches and Islands provide excellent opportunities for specific placement of monitoring instruments, with the possibility of direct observation of undisturbed soil material. Borehole Monitoring is more flexible with respect to depth of installation than the other three strategies. Maintenance of monitoring instruments in the Monitoring Trenches and Borehole Monitoring is not always possible because instruments are often backfilled in place. Some techniques used to support the Geophysical Monitoring strategy (e.g., electroresistive borehole tomography) suffer from the same infeasibility. Instrument maintenance in the Monitoring Islands is easier if the island is not backfilled. Limiting access to undisturbed soil, especially with respect to the Monitoring Trenches and Borehole Monitoring strategies, will also make instrument replacement more difficult. Portability of surface geophysical instruments used during the infiltration experiments removes several restrictions on maintenance and replacement.

The document also presents the concept of primary performance measures (e.g., water content, water tension and solute concentration), each of which directly influences water movement and contaminant migration from disposal sites. The majority of commercially available monitoring instruments measure secondary performance measures, which are soil water conditions that are converted to primary measures using calibration curves. Unfortunately, each instrument has different operational limitations and sensitivities, which depend on the soil water environment. Therefore, it is recommended to use multiple instruments whose data convert to the same primary performance measures. This should improve the confidence that changes in soil water conditions are real and not affected by the monitoring systems themselves.

# CONTENTS

# Figures

# Tables

# Executive Summary

U.S. Nuclear Regulatory staff identified a need for research to better assess unsaturated zone monitoring techniques and strategies applicable to LLW disposal facilities. A field work plan was developed and implemented at the Maricopa Environmental Monitoring site (Maricopa, AZ) where two field-scale infiltration experiments were conducted. A companion NUREG (i.e., NUREG/CR-5694) presents the results of the field experiments with respect to water movement and tracer migration.

This document discusses the need for redundancy in the monitoring of primary performance measures (e.g., water content, water tension and solute concentration). Each of these performance measures directly influences water movement and contaminant migration from disposal sites. Almost all monitoring instruments provide data on secondary measures, which are converted to primary measures using calibration curves. Using more than one instrument to convert data to the same primary performance measure, can compensate for limitations and sensitivities of each instrument.

This document also describes and compares four monitoring strategies that were implemented at the site. The strengths and weaknesses of each strategy were described with respect to installation, maintenance and replacement of monitoring systems and instruments. The comparisons stem directly from insights gained during the field experiments, and from the work of others. The comparisons are qualitative in nature, so that they are not influenced by the specific characteristics of the Maricopa site. The four strategies follow:

1. Monitoring Trenches consist of potentially long, wide or narrow trenches, into which instruments can be installed. Once opened, the trench provides direct access to the soil or engineered material. The material can be sampled and described easily. Instruments can be precisely placed and visually inspected for completion. Wiring and electrical connections can be placed in conduit and protected from environmental degradation. However, maintenance and replacement of instruments in the trench are limited after the trench is closed.

2. Monitoring Islands consist of large diameter boreholes drilled vertically into the soil, allowing monitoring instruments to be installed into undisturbed material. Culverts are placed vertically in the these boreholes for access and to prevent cave in of the soil. This strategy permits monitoring of vertical transects of soil water conditions, because the islands can be installed to depths exceeding 10 m. However, the horizontal spatial resolution is limited because instruments must be installed close to the island wall. Instrument maintenance and replacement are easier than for the other strategies which rely on fixed, subsurface instruments.

3. Borehole Monitoring consists of vertical and horizontal boreholes used for monitoring. Using portable probes (e.g., neutron probe), spatial and depth resolution of data can be excellent. Fixed point devices can be installed in the borehole, enhancing the redundancy of monitoring for primary performance measures. Maintenance and replacement of portable probes is not an issue with this strategy, but is very difficult for permanently-installed instruments.

4. Geophysical monitoring consists of a combination of intrusive and non-intrusive techniques for measuring bulk electrical properties of subsurface material. The data cannot easily be converted to primary performance measures, and could require a significant amount of ground-truthing. However, portability of non-intrusive instruments (e.g., EM-31 and EM-38) permits rapid data collection. Intrusive techniques used at the Maricopa site (e.g., electroresistive tomography) can provide 2-D tomograms of electrical properties, which were shown to change with water content. Maintenance of ERT boreholes is not practical, requiring complete replacement.

We identified 12 subgoals for the monitoring program, all of which are compatible with the three major goals described in Section 2. The subgoals are intended to better define the important aspects of the monitoring program and how or whether use of the monitoring strategy can address the subgoal. We also included a section that deals with site conditions and processes and how they affect the choices of possible monitoring strategies. We further subdivided these into natural (e.g., precipitation, depth to water table) and anthropogenic (e.g., presence of buildings) conditions. A total of 12 site conditions were identified and opposing conditions were defined (e.g., shallow/deep water table). We then categorized each strategy as to whether the condition supported its use, weakened its use, or made no difference with respect to its use. When used in combination with the subgoals, the choice which strategy (or combination of strategies) to use becomes more clear.

# FOREWORD

This technical report was prepared by the Department of Soil, Water and Environmental Science at The University of Arizona (UAZ), under its research project with the Radiation Protection, Environmental Risk and Waste Management Branch in the Office of Nuclear Regulatory Research (Contract No. NRC 04-95-046). The research objectives were to: assess capabilities, limitations, and usefulness of alternative techniques for monitoring moisture movement and contaminant transport in the unsaturated zone; provide technical bases for identifying and evaluating appropriate techniques for unsaturated zone monitoring; and test monitoring strategies and instrumentation on a variety of field scales using actual water and tracer applications and geometries. The research was requested by the Office of Nuclear Material Safety and Safeguards to provide technical information and bases for licensing reviews.

This report, NUREG/CR-5698, describes the principal lessons learned from the field study to evaluate alternative monitoring strategies and related instrumentation. Specifically, four monitoring strategies were evaluated at the Maricopa Environmental Monitoring site. The evaluation of these strategies focused on their inherent strengths and weaknesses with respect to installation, maintenance, and replacement of monitoring systems that support the four monitoring strategies.

Detailed research results and data from the field studies conducted over a three-year period are provided in a companion report, NUREG/CR-5694 (Young et al., 1999). NUREG/CR-5694 provides the technical bases for identifying and evaluating the four monitoring strategies and related instrumentation.

Information in both NUREG/CR-5694 and this report may be useful to those involved in designing or reviewing monitoring programs for water and contaminant movement at low-level radioactive waste and decommissioning facilities. Two workshops were conducted by the UAZ investigators: a "hands-on" technology transfer workshop held at the Maricopa field site in February 1998; and a "lessons learned" seminar held at NRC Headquarters auditorium in July 1998. Agreement State regulators and their contractors were notified of the workshops, and attended along with scientists from other Federal agencies, DOE national laboratories, universities and industry.

NUREG/CR-5698 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 purposes only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein.

# Acknowledgments

This research was supported by the U.S. Nuclear Regulatory Commission, under Contract No. 04-95-046. The authors would like to thank peer reviewers Glendon Gee, Phil Meyer, and Mark Rockhold of Pacific Northwest National Laboratory for their insights, discussions and comments.

# List of Abbreviations

| | |
|---|---|
| 2-D | Two dimensional |
| 3-D | Three dimensional |
| AC | Alternating Current |
| DC | Direct Current |
| E-W | East-West |
| EC | Electric conductivity |
| $EC_a$ | Apparent Electrical Conductivity |
| EM | Electromagnetic Induction |
| EM-31 | Electromagnetic induction at intermediate depth (3 to 6 m) |
| EM-38 | Electromagnetic induction at shallow depth (0.75 to 1.5 m) |
| EM-39 | ERT borehole device |
| ERT | Electroresistive Borehole Tomography |
| GPR | Ground-penetrating Radar |
| HDS | Heat Dissipation Sensors |
| LLW | Low-level waste |
| MAC | Maricopa Agricultural Center |
| MEM | Maricopa Environmental Monitoring |
| N-S | North-South |
| NRC | U.S. Nuclear Regulatory Commission |
| PVC | Polyvinyl Chloride |
| RFP | Request for Proposal |
| SD | Standard Deviation |
| SDMP | Site Decommissioning Management Plan |
| TDR | Time Domain Reflectometry |
| $\theta_v$ | Volumetric water content |

# 1 INTRODUCTION AND OBJECTIVES

## 1.1 Motivation

In September, 1994, the U.S. Nuclear Regulatory Commission (NRC) issued a Request for Proposal (RFP) to assess unsaturated zone monitoring techniques and strategies applicable to low-level radioactive waste (LLW) disposal facilities. The RFP stemmed from a request by NRC staff for additional information on monitoring systems and strategies that could be used for evaluating future disposal site applications. This research was later expanded so that it would be relevant to sites located primarily in the humid, eastern portion of the US.

Unsaturated zone monitoring to detect releases of radionuclides is an important safety issue at LLW disposal facilities. The unsaturated zone is a primary component that isolates near surface waste from underlying ground-water systems. Monitoring can be used to show that facilities are operating safely during waste emplacement and after site closure. Effective unsaturated zone monitoring requires choosing instruments and installation procedures, and integrating them into an overall program that incorporates: 1) the results of site characterization, 2) operational limits for each device, 3) frequency of data collection, and 4) the need for performance confirmation of the site. This document reports on comparisons made of four monitoring strategies that were used in a large field study at the Maricopa Environmental Monitoring site (called the Maricopa site). The results of the field studies are summarized by Young et al. (1999).

## 1.2 Goals of the Field Studies

There were three broad goals for the field study portion of this contract: 1) to construct a field site in which monitoring strategies could be evaluated through a series of water flow and solute transport experiments; 2) to evaluate the use of several strategies for monitoring flow and transport in the unsaturated zone at both arid and humid sites; and 3) to be able to address the specific objectives as listed below:

1. Assess capabilities, limitations, and usefulness of alternative techniques for monitoring water movement and contaminant transport in the unsaturated zone of humid and arid areas.
2. Provide the technical basis 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.

## 1.3 Brief Description of Field Studies

The study developed and tested monitoring strategies which can be used for a variety of LLW conditions. Only the subsurface transport pathway was considered. The original field testing plan (Young et al., 1996) described some of the supporting factors that were considered during the design phase of this project.

Subsequent field activities were conducted at the Maricopa Agricultural Center, Maricopa, AZ (Figure 1.3-1). The Center, located about 42 km southwest of Phoenix, is in the northwestern portion of Section 20, 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 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

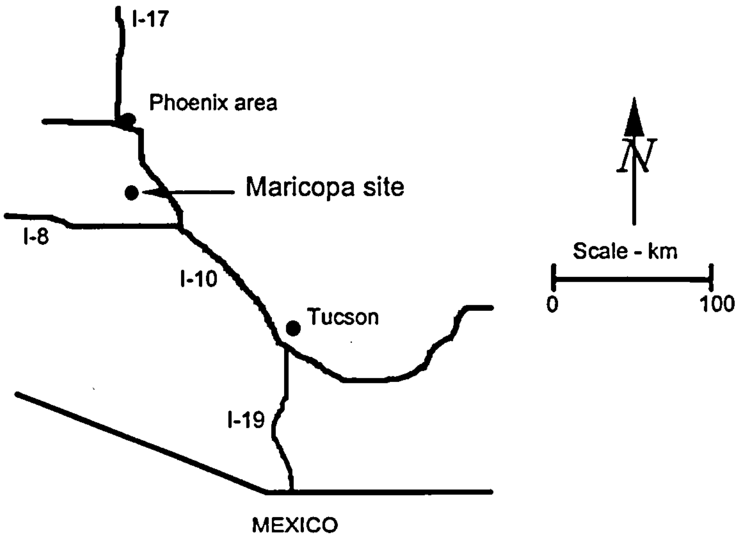


Figure 1.3-1. Index map for Maricopa site.

variability with lenses of material ranging from gravelly to clayey textures. At Field 115, where the research was conducted, the fine-loamy soil is classified as a Casa Grande soil (fine-loamy, mixed, hyperthermic Typic Natrargids) (Post et al., 1988).

The field research was conducted on a 50 m by 50 m plot located within a 0.9 hectare field. Irrigation canals exist at the southern and eastern boundaries of the site, a flood-irrigated alfalfa field is located to the north and an access road is located to the west. A support zone is located between the irrigated plot and the access road, where components of the irrigation system (e.g., solenoids, timers, valves and piping) were installed. All basic utilities (e.g., AC power, water, land-line telephone) were made available through either the agricultural-center infrastructure or on-site construction. This allowed AC power, for example, to be installed throughout the plot for a variety of uses.

The irrigation system was designed specifically for conducting flux-controlled infiltration experiments. It consisted of self-cleaning precision drip emitters (0.6 gallon/hour, Netafim Techline, Fresno, CA), placed on a 0.3 m by 0.3 m grid over the 2500 m$^2$ area of the plot. Nearly 27000 emitters were used. A total of 164 drip lines were cut to a length of 50 m, and then connected to manifolds on either end of the plot. The system was divided into six, nearly identical, irrigation stations. Water application was measured using two precision flow meters (McCrometer, Hemet, CA) placed in series immediately before entering the individual stations. After installing and testing the irrigation system, 0.8 mm thick Hypalon pond liner was placed over the field plot, extending at least 5 m beyond the irrigated area. The pond liner was used to eliminate evaporation from the soil.

Two experiments were conducted at the site covering the time frame from Spring 1997 through Summer 1998. During Experiment 1, water at an average rate of 1.85 cm d$^{-1}$ was applied to the soil for 23 days for a total application of 44.4 cm. Bromide was added as a tracer for the first 15 days. Redistribution was monitored for 69 days before the experiment ended. During Experiment 2, water at an average rate of 1.97 cm d$^{-1}$ was applied for 33 days for a total application of 64.8 cm. Salt (NaCl) was added as a tracer for the first 7 days. Redistribution was monitored for 177 days before field experiments at the site ended on July 1, 1998. A complete discussion of results for the field experiments is available (Young et al., 1999). Table 1.3-1 lists the basic boundary conditions for the full suite of field experiments at the Maricopa site.

## 1.4 Brief Description of Monitoring Strategies

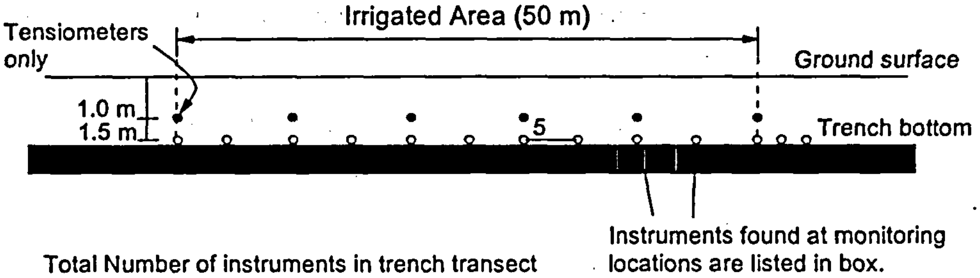
The field plot incorporated a variety of monitoring strategies, which form the basis for comparisons in this research. They are designated as monitoring trench, monitoring island, borehole monitoring, and geophysical monitoring. Briefly, each monitoring strategy consists of the following:

1 Monitoring Trench - This strategy used an excavated trench, into which monitoring instruments were installed. A total of 13 instrument clusters were chosen, which are located in a N-S transect, parallel to the horizontal neutron probe access tubes, with offsets of 2.5 and 5.0 m (Figure 1.4-1 is a schematic of the trench). The majority of instruments were installed at 1.5 m depth, though a few were installed at 1.0 m and closer to ground surface. Instrument wires, cables and tubes were brought to ground surface, placed in conduit and taken to data loggers and manifolds placed at key locations on the irrigated plot.

2. Monitoring Islands - This strategy used two large diameter boreholes (1.7 m diameter), into which highway culverts (1.5 m diameter) were lowered to a depth of 3 m. The annular spaces were then backfilled using sieved soil. The bottoms of the culverts were left open to the bare soil surface and the top was closed with a plywood lid. Three vertical transects of instruments were installed in each island. Two transects were equipped with clusters of four instruments installed at offsets of 50 cm to 300 cm depth, and approximately 50 cm into undisturbed soil. The third transect was instrumented at 100 cm offsets, but the instruments were installed in the annular space between the culvert and the undisturbed soil; this was done to observe potential preferential flow through the repacked soil material. A total of 18 instruments of each type were installed in each island. All

Table 1.3-1. Summary of experimental conditions at the Maricopa site.

| | Experiment 1 | Experiment 2 | Experiment Totals |
|---|---|---|---|
| | Water | Water | |
| Start Date: | 4/28/97 | 12/3/97 | |
| End Date: | 5/21/97 | 1/5/98 | |
| Duration: | 24 days | 34 days | 58 days |
| Application Rate: | 1.85 cm $d^{-1}$ | 1.97 cm $d^{-1}$ | |
| Depth Applied: | 44.4 cm | 64.8 cm | 109.2 cm |
| | Bromide | Total conductivity (salts) | |
| Start Date: | 4/28/97 | 12/3/97 | |
| End Date: | 5/11/97 | 12/9/97 | |
| Duration: | 14 days | 7 days | |
| Mean Concentration: | 31.6 ppm | 2.2 dS $m^{-1}$ | |
| Depth Applied: | 26 cm | 14 cm | |



Total Number of instruments in trench transect

| | |
|---|---|
| Thermocouple Psychrometer | 13 |
| Tensiometer | 19 |
| TDR Probe | 13 |
| Heat Dissipation Sensor | 13 |
| Stainless Steel Solution Sampler | 13 |

Figure 1.4-1. Monitoring instruments installed at buried trench transect.

instruments were connected to data loggers or vacuum systems using multiplexers and manifolds, respectively.

3. Borehole Monitoring - This strategy relied on conventional and unconventional borehole installation and usage. Vertical boreholes were installed at regular intervals throughout the plot to observe infiltration of water into the soil using a variety of instruments. The boreholes were installed by advancing a 10.2 cm diameter auger to target depths of either 3 m or 15 m, depending on the location and the use of the borehole. A total of 41 access tubes were used for vertical neutron probe monitoring, and 13 were used for ground water monitoring; 27 tubes each were used for permanently-installed tensiometers and soil solution sampling; and 12 were used for electroresistive borehole tomography (ERT), also used to support the geophysical monitoring strategy. Three horizontal access tubes were also installed (2 N-S and 1 E-W) for neutron logging.

4. Geophysical Monitoring - This strategy relied on surface and subsurface monitoring of bulk electrical conductivity or resistivity. A total of 90 surface locations were chosen on a grid and used for electromagnetic induction surveys (e.g., EM-31 and EM-38) of changes of bulk electrical conductivity ($EC_a$). Subsurface monitoring was also done using ERT, mentioned in the Borehole Monitoring description. For the ERT methodology, 12 boreholes were advanced to 15 m each, and equipped with sources/detectors at 1 m vertical offsets. Together the EM and ERT techniques provided data and information on changes of bulk soil $EC_a$, caused primarily by changes in water content.

As can be inferred from the above descriptions, the monitoring systems (which encompass access ports, instruments and data collection systems) can be used to support more than one strategy. For example, the ERT system is part of the Geophysical Monitoring strategy, but was installed in boreholes, so it can be considered an overlap. Likewise, the horizontal access tubes used for neutron probe logging were installed in monitoring trenches, so this system overlaps the Monitoring Trench and Borehole Monitoring strategies. These overlaps improved the design flexibility of the overall field plot.

# 2 ASPECTS OF UNSATURATED ZONE MONITORING AT DISPOSAL FACILITIES

## 2.1 Definitions of Monitoring

For the purposes of this document, monitoring means "observing and making measurements to provide data to evaluate the performance and characteristics of the disposal site" (U.S. NRC, 1998a). Though this definition is somewhat self-explanatory, the difficulty lies in the details of designing a monitoring system to accommodate the myriad of disposal site environments and designs, so that the discrete observations can be used for evaluating the performance of disposal sites. We are limiting the extent of monitoring to unsaturated soil and geological material immediately outside of the waste containment structure itself, and on detecting and quantifying the rate and volume of either water or contaminant movement, or both, released from containment cells (e.g., a trench, concrete bunker, landfill, etc.) to the undisturbed environment. Many aspects of monitoring, which are discussed here, can be used for observing changes in engineered material, but this is a secondary benefit.

Throughout this document, we refer to phases of monitoring programs, including preoperational, operational and postoperational (or post-closure) phases. In these references, we also make a distinction that site characterization has been completed, and that the basic environmental characteristics and processes have been defined well enough for the site to be licensed. Preoperational monitoring refers to measurements made prior to waste emplacement at the facility, including monitoring to support site characterization (before submitting license application). Operational monitoring refers to measurements made from the beginning of facility construction through the period when waste is no longer accepted. Postoperational monitoring begins when the facility no longer accepts waste material and continues until the custodial care period ends. Much of the document addresses operational and postoperational monitoring phases.

Monitoring subsurface environments is achieved through the implementation of conceptual frameworks and related physical components. Thus, the monitoring program is a set of monitoring strategies, including data collection intervals, analytical methods and data analysis. Data collection intervals are important aspects of both spatial and temporal sampling; obviously, a larger number of sampling points could improve the likelihood of detecting releases from the containment unit, or other environmental changes which could signify a potential future release. Likewise, sampling at a higher temporal rate permits the quantification of seasonal variability and other time-dependent behavior. Methods and statistical procedures are available to evaluate the data, and to make conclusions with respect to facility performance. Aspects of conceptual frameworks for ground-water quality monitoring (e.g., Franke et al., 1997) can be tailored for site-specific monitoring at LLW sites, especially those that relate to the preparation of long-term monitoring programs, subsequent review and evaluation of monitoring goals, and modification of the monitoring program to address changes in goals and objectives.

Embedded into the monitoring program are monitoring strategies, which we define as a set of monitoring systems that emphasize and support a specific concept or philosophy. Numerous combinations of philosophies can be proposed, depending on the site characteristics and the goals of the monitoring program, and this document will not attempt to generate an exhaustive list. However, emphasizing 1) intrusive versus non-intrusive methods; 2) manual versus automated data collection and 3) direct or indirect sampling, or combinations thereof could be used for guiding the design and implementation of the monitoring program. Judicious choices of monitoring strategies must be made early in the design process, because subsequent reviews of monitoring goals could change the monitoring emphasis. Therefore, the best combination of strategies would be one that addresses potential dovetailing of monitoring goals during different phases of site monitoring.

A monitoring system is defined as a system that collects the output of sensors (Dictionary of Science and Technology, 1992). The monitoring system supports the monitoring strategy. The monitoring system includes the sensor itself, wiring or cabling, data loggers, and other components that support the data collection. At the Maricopa site, significant effort was spent on designing the ancillary components of the monitoring system, such as electrical conduits, AC power for the data loggers, etc.

A monitoring instrument is a device or sensor that collects information about the site environs. It is only that portion which measures some physical or electrical soil condition. For example, the tensiometer is composed of a ceramic cup, two lengths of plastic tubing, a rubber stopper and a pressure transducer, which is then connected to a data logger through electrical wiring. For the purposes of this document, only the ceramic cup and plastic tubing are considered part of the instrument; we include the pressure transducer and wiring as part of the monitoring system.

## 2.2 Definition of Performance Measures

We define performance measure as a primary soil water parameter which directly relates to water movement and contaminant migration from a disposal area. We designated soil water tension, soil water content and pore water concentration of some target constituent as performance measures. Soil water tension influences the direction and magnitude of the hydraulic gradient. Soil water content influences the hydraulic conductivity and acts as the primary medium which transports contaminants. Pore water concentration represents the source of contamination; numerical concentration levels are often incorporated into environmental regulations, where exceedances could trigger some level of enhanced monitoring or other corrective action.

Primary performance measures are differentiated from secondary measures by the use of instruments which use indirect measures and calibration curves. Considering soil water content, for example, the TDR and neutron probe methods measure dielectric constant and hydrogen ion concentration, respectively. These secondary parameters are then converted to water content by way of calibration curves, using the secondary parameter as independently measured and the performance measure as the dependent parameter. In this way, water content is obtained from the TDR dielectric constant using, e.g., Ledieu's (1986) equation ($\theta_v = b_0 + b_1\epsilon^{½}$), where $\theta_v$ is the volumetric water content and $\epsilon$ is the dielectric constant. Different forms of calibration curves may be used for other instruments.

Throughout the Maricopa field work and this document, we stressed the need to monitor each of the three performance measures during the development of the field program. Each of the four monitoring strategies incorporated this philosophy, to the extent possible. Instruments in the monitoring trench strategy, for example, measured soil water content using TDR and the neutron probe; soil water tension using tensiometers, HDS units, and thermocouple psychrometers; and solution concentration using pore water samplers and destructive soil sampling. Each of these devices have specific ranges of operation and sensitivities that span soil water conditions that we expected in the field (i.e., from very dry to very wet). Field observations during Experiments 1 and 2 would have been limited if we had relied heavily on only one or two monitoring systems; our field conclusions would have been limited also.

## 2.3 Goals of Subsurface Monitoring

We define three goals for subsurface monitoring programs which can be applied at actual disposal sites. They are:

1. To provide early warning of releases of contaminants (e.g., radionuclides) from disposal sites before they reach the facility boundary (U.S. NRC, 1998b).

This goal, paraphrased from NRC regulation (10 CFR 61.53), applies to monitoring programs during facility operation and after facility closure.

2. To design a system that reduces or eliminates active maintenance, emphasizes protection of the facility during potential future replacement of instruments, and allows for consistent monitoring of site conditions throughout different monitoring phases

Monitoring programs should be designed to avoid the use of monitoring strategies or systems that will require significant maintenance and replacement actions throughout the lifetime of the program. The need to disrupt engineered cover material during instrument replacement introduces enhanced risk of failure of the containment unit. The use of instruments that require active maintenance (e.g., certain types of tensiometers) could be problematic if the facility is closed and technical staff need to come to the site often.

3. To use strategies that focus on redundant observations of performance measures, reducing the dependency of the program on a single monitoring system.

Describing complex, subsurface phenomena with instruments that monitor only a few secondary parameters increases the risk that instrument range or sensitivity will reduce the effectiveness of the instrument and, thus, the effectiveness of the monitoring program. For this reason, we believe that the flexibility of the monitoring program is enhanced by emphasizing redundancy in the measurement of performance measures by using multiple instruments.

## 2.4 Role of Monitoring in Performance Confirmation

Performance confirmation, for the purposes of this document, is defined as the program of tests, experiments, and analyses which are conducted to evaluate the accuracy of the information used to determine facility compliance (U.S. NRC, 1998c). Elements of performance confirmation, originally designed for the high-level waste disposal program, can be used for LLW sites as well.

Goal #1, listed in Section 2.3, is to monitor the subsurface environment in such a way that releases are detected before they reach the facility boundary. Releases to the subsurface environment are based on changes in soil water conditions (content or tension) or contaminant concentration as they relate to baseline conditions at the site. The data supplied by the monitoring program thus provides information about the integrity of the disposal unit, and whether or not elements of the disposal site are functioning as intended and predicted. The program used for unsaturated zone monitoring, during and after waste emplacement, must be capable of detecting changes to subsurface conditions, greater than those expected during the license review. Therefore, the long-term monitoring program needs to be designed so that it does not adversely affect the natural and engineered elements of the disposal site, and so that it can operate without the need for significant and active maintenance, because this could affect the ability of the program to perform adequately.

# 3 DESCRIPTION OF MONITORING STRATEGIES

## 3.1 Characteristics of Strategy and Collected Data

### 3.1.1 Monitoring Trench Strategy

The monitoring trench strategy uses either one or a series of shallow trenches excavated from native soil or backfill material. Two types of trenches can be envisioned: a wide trench excavated with backhoe or other heavy equipment, and a shallow trench excavated with ditching equipment. The wide trenches allow unfettered access to the soil profile, allowing site personnel to sample the material, install monitoring instruments through the trench wall, or simply visually observe the material. Narrow trenches greatly restrict the ability of site personnel to view the soil profile and install instruments in the trench wall, but they can be very quickly excavated, and with relatively little site disturbance.

With a the wide trench, layering and textural characteristics of the profile are easy to view and describe. During trench construction at the Maricopa site, a soil scientist described the morphology of the profile, identifying layering, textural discontinuities, the presence of calcic horizons, and soil structure. Numerous grab samples were collected from the bottom of the trench so that spatial variability of texture along the N-S transect could be described. Nearly 70 undisturbed core samples were collected and analyzed for soil hydraulic properties. The ability to "walk through" the soil profile for upwards of 60 m (in our case) greatly enhanced our understanding of the shallow soil profiles at the Maricopa site. The trench was excavated to only 1.5 m, very shallow when considering deep vadose zones in semi-arid regions. Excavation could have been deeper, but a practical limitation exists for the depth of excavation because of wall stability and worker safety issues.

A wide trench permits monitoring instruments to be installed laterally into undisturbed soil material or engineered covers. During our experimental setup, 81 sensors were placed 1.5 m into undisturbed soil, and one horizontal neutron probe access tube was placed onto the trench floor (Table 3.1-1 and Figure 1.4-1). Of course, additional sensors could have been used, and indeed many more sampling points might be necessary to monitor water flow at an actual disposal site. All electronic sensors (e.g., TDR, HDS, thermocouple psychrometers) were connected to data acquisition equipment for remote data collection. Thus, a large amount of data and information can be collected without the presence of site personnel or the potential problems of worker error.

Two narrow trenches were added to the sampling program, into which we lowered horizontal neutron probe access tubes. The ability to collect data along a single transect, at spatial offsets of (in our case) 0.25 m, greatly offsets the disadvantage of requiring on-site personnel during data collection. We concluded that use of these horizontal access tubes could benefit monitoring programs at actual disposal sites.

### 3.1.2 Monitoring Islands Strategy

The monitoring island strategy, as used in this research, utilized large diameter (1.53 m) highway culverts, permitting access to undisturbed soil material for sampling and surveillance. The culverts were advanced to only 3 m depth, still relatively shallow in a deep vadose zone environment. In practice, the depth of the island is limited by the drilling equipment.

The island strategy has several unique characteristics. It provides the site personnel with direct access to deep soil material, much deeper than practical with the trench strategy. Before the island material is lowered into the borehole, the soil profile is exposed and can be described or sampled in any direction radially from the borehole. Once the island material is placed in the borehole and backfilled, the choices of location and numbers of monitoring instruments are quite flexible and can be tailored for specific goals of the monitoring program. The use of vertical transects allows site personnel to observe and quantify hydraulic gradients, and therefore the direction of soil water movement, which is complex near the soil surface. The strategy can be used to achieve a variety of goals depending on disposal site characteristics. The monitoring island concept has been used by other research

Table 3.1-1. Summary of monitoring devices and monitored environment in buried trench.

| Device | Fundamental measure | Performance measure | Number of points or length | Total number of points |
|---|---|---|---|---|
| Horizontal neutron logging | Hydrogen ion concentration | Water content | 3 x 58 m | ~ 699 |
| Time domain reflectometry | Soil bulk dielectric | Water content | 13 | 13 |
| Tensiometers | mV response | Water tension | 19 | 19 |
| Heat dissipation sensors | Temperature change | Water tension | 13 | 13 |
| Thermocouple psychrometers | Soil humidity | Water tension | 13 | 13 |
| Solution samplers | Soil pore water | Solute concentration | 13 | 13 |
| Temperature thermocouples | Voltage | Soil temperature | 10 | 10 |
| Soil sampling | Soil material | Soil texture,<br>water content,<br>solute concentration | 213 | 213 |

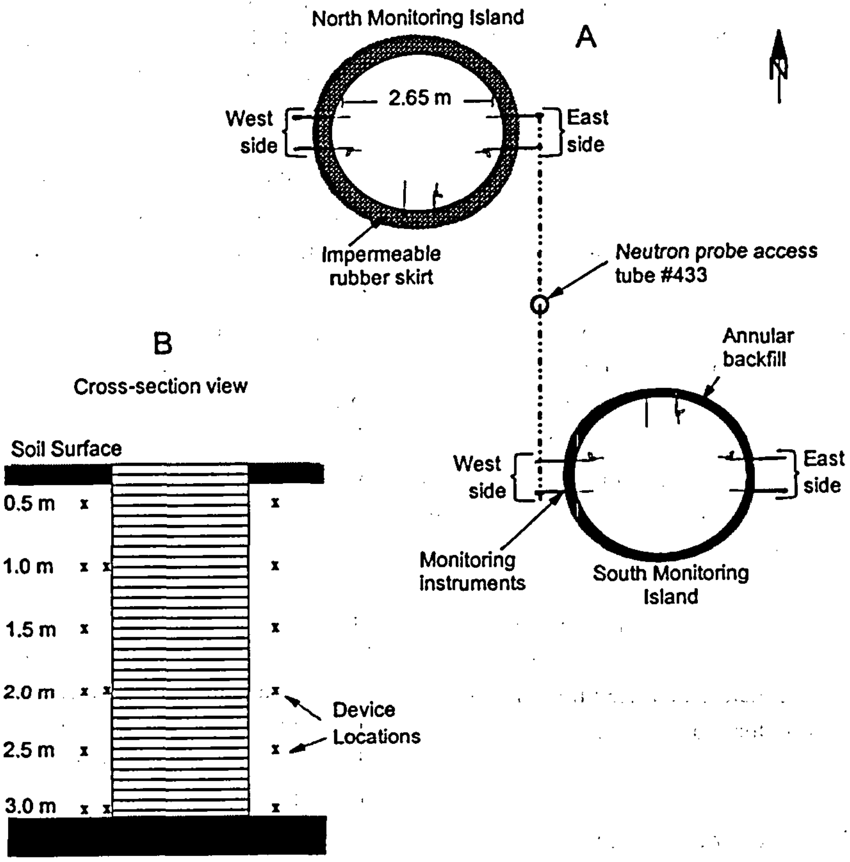


Figure 3.1-1. Cross-section (A) and map view (B) of monitoring island and instrument orientation.

groups (e.g., Scanlon et al., 1997), though in a slightly different form. Though only two islands were used at the Maricopa site, disposal site monitoring programs could benefit through the use of multiple islands, placed either adjacent to or inside the disposal zone.

At the Maricopa site, we installed clusters of instruments in three vertical transects, each offset by 90° and 50 cm depth (Table 3.1-2 and Figure 3.1-1). Similar to the monitoring trench, all electronic sensors were sampled using data acquisition equipment, so the rate of data collection was higher than would be possible if collected manually. Only the solution samplers required on-site personnel when active. All of the 15 samplers per island were connected to a single vacuum manifold, greatly reducing staff effort during sample collection. Textural samples were also collected.

### 3.1.3 Borehole Monitoring Strategy

The borehole monitoring strategy – probably the oldest strategy used for subsurface monitoring – involves the excavation of small diameter boreholes with standard drilling equipment (e.g., hollow-stem auger). During the drilling activities, grab or core samples can be collected at a rate specified by technical personnel. The depth of drilling is limited by the type of drilling method and size of the drilling rig; generally, the boreholes can be advanced to any depth necessary. Thus, the borehole monitoring strategy represents the only strategy which is not depth limited. Monitoring programs have historically used this strategy because of the need to monitor ground water quality at disposal sites.

This strategy is flexible with respect to the number of boreholes that can be advanced at a particular site, and the method of advancement. Because drilling rigs are small and mobile, they can be used for excavating boreholes in a wide range of surface conditions, at spatial offsets that are quite small (in the case of the Maricopa site, many of the boreholes were spaced 1 meter apart). Surface conditions are kept relatively undisturbed during the drilling process because only a small volume of cuttings are returned to ground surface. A wide variety of drilling methods are available depending on the subsurface environment encountered at a particular site (Driscoll, 1986), and the restrictions on subsurface introduction of fluids.

Once the borehole is advanced, site personnel can design the monitoring program to include either mobile or fixed monitoring points. Both were used at the Maricopa site (Table 3.1-3 and Figure 3.1-2). Mobile points include the neutron probe or water level indicators. Probes are lowered into the borehole, readings are taken, and the probe is removed. In the case of the neutron probe, is held stationary in the borehole during a reading, and then advanced as needed. Other probes are raised or lowered for continuous data collection, such as for the downhole EM-39 method. Therefore, the site personnel have complete discretion on the vertical resolution of measurements needed.

When the sampling points are fixed in space, such as the deep tensiometers and dual-chamber solution samplers, the flexibility with respect to vertical resolution is lost. Moreover, a practical limitation exists on the number of sampling points that can be fixed inside each borehole. However, this disadvantage is offset by the fact that direct measurements of performance measures can be taken. Recent advances in subsurface monitoring have led to the development of tensiometers and solution samplers which can be installed to any depth. The neutron probe method, though very useful, is sometimes disparaged because of the need for onsite calibration, a difficult procedure to conduct accurately. However, on site calibration is not critical where the main interest is in water content changes. Data collection using tensiometers is automated, so that site personnel are not needed. These fixed point monitoring instruments can supplement the neutron probe method, as done during this research.

### 3.1.4 Geophysical Monitoring Strategy

The geophysical monitoring strategy involves the measurement of bulk electrical properties of soil or geological material, and the conversion of the data to water content or salinity. Instruments can be categorized as surface or subsurface. Both types were used at the Maricopa site (Table 3.1-4 and Figure 3.1-3). The surface instruments (e.g., EM-31 and EM-38) are used for obtaining electrical conductivity readings to depths between ground surface and approximately 4-6 m, depending on the device

Table 3.1-2. Summary of monitoring devices and monitored environment in monitoring island strategy.

| Device | Fundamental measure | Performance measure | Number of points or length | Total number of points |
|---|---|---|---|---|
| Time domain reflectometry | Soil bulk dielectric | Water content | 30 | 30 |
| Tensiometers | mV response | Water tension | 30 | 30 |
| Heat dissipation sensors | Temperature change | Water tension | 30 | 30 |
| Solution samplers | Soil pore water | Solute concentration | 30 | 30 |
| Soil sampling | Soil material | Soil texture, water content, solute concentration | 12† | 12 |

† Represents only those samples collected before irrigation phases of either experiment.

Table 3.1-3. Summary of monitoring devices and monitored environment in borehole monitoring strategy.

| Device | Fundamental measure | Performance measure | Number of points or length | Total number of points |
|---|---|---|---|---|
| Vertical neutron probe | Hydrogen ion concentration | Water content | 34 x 3 m<br>10 x 11 m | 848 |
| Tensiometers | mV response | Water tension | 27 | 27 |
| Solution samplers | Soil pore water | Solute concentration | 27 | 27 |
| Monitoring wells | Water level, ground water | Gradient, solute concentration | 13 | 13 |
| Soil sampling | Soil material | Soil texture, water content, solute concentration | 159 | 159 |

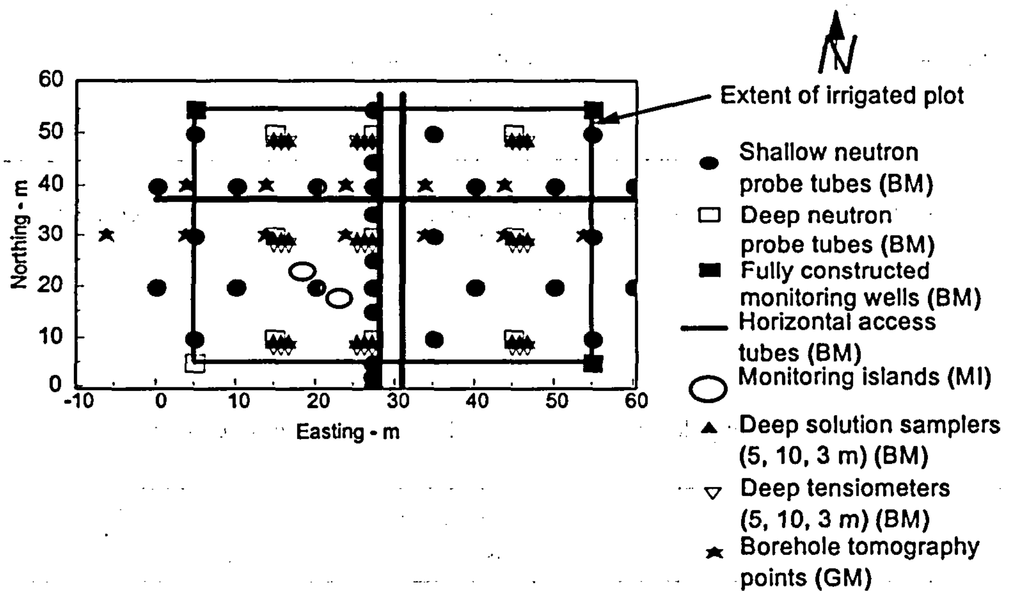


Figure 3.1-2. Schematic field plot, showing the location of major monitoring systems. Monitoring strategy designation is listed in the legend; MT is monitoring trench, MI is monitoring islands, BM is borehole monitoring, and GM is geophysical monitoring. Note that EM-31 and EM-38 monitoring points (90 total) are not shown.

Table 3.1-4. Summary of monitoring devices and monitored environment in geophysical monitoring strategy.

| Device | Fundamental measure | Performance measure | Number of points or length | Total number of points |
|---|---|---|---|---|
| EM-31 | Bulk $EC_a$ | Change in water content or salinity | 90 | 180 |
| EM-38 | Bulk $EC_a$ | Change in water content or salinity | 90 | 180 |
| Electroresistive borehole tomography | Electrical resistivity | Change in water content or salinity | 10 x 15 m | n/a† |

† Borehole tomography method provides 2-dimensional representations of electrical resistivity; therefore, the number of discrete points cannot be defined.

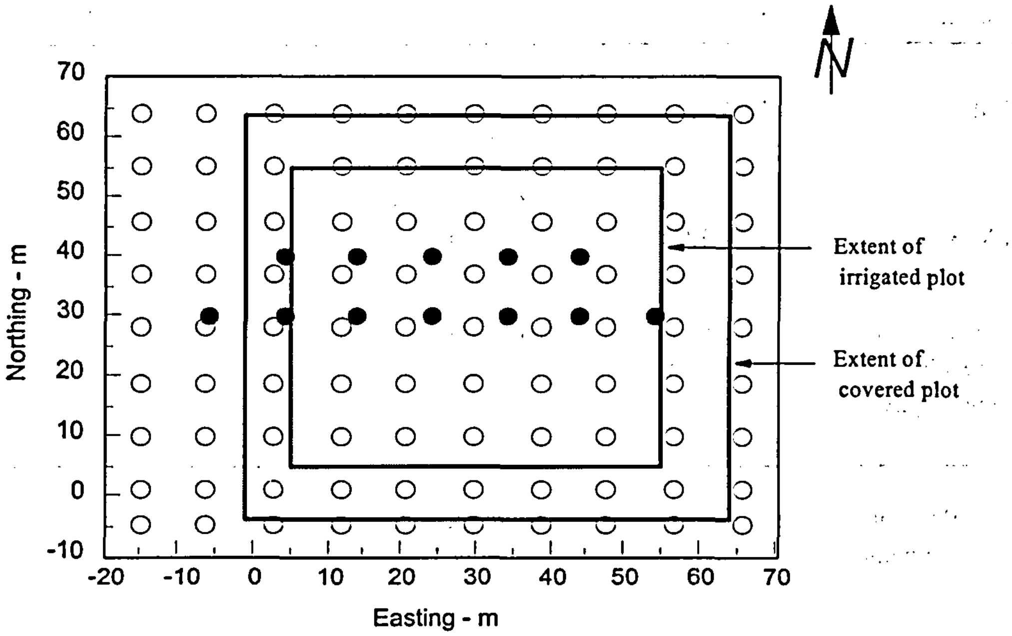


Figure 3.1-3. Locations used for surface electromagnetic induction surveys and for ERT studies. Open circles represent the EM points and closed circles are the ERT boreholes.

and orientation. The EM instruments are carried from point to point across the plot, and placed on the ground surface. The EC value is then read manually or recorded digitally with a data logger. The subsurface ERT device is combined with the borehole monitoring strategy and measures electrical resistance. Electrical conductors were installed on the outside of PVC pipe, and permanently installed inside augered boreholes. Data collection requires site personnel to run a series of computer programs that operate the field equipment.

For EM measurements, field personnel are required to be present during data collection. Because the instruments are either placed on the ground or kept at hip level, they can be used without disturbing surface soil or engineered material. This allows the monitoring program to utilize this method during post-closure time periods. The ERT method is considerably more complicated to use, and requires highly trained field personnel to collect and analyze the data. However, the method provides 2-D or 3-D tomograms of electrical resistance, as opposed to the neutron probe method, which only provides one-dimensional measurements. The tomograms can provide valuable insights of layering and soil electrical properties, which is related to water content.

## 3.2 Strengths and Weaknesses with Respect to Monitoring Objectives and Data Analysis

### 3.2.1 Monitoring Trench Strategy

Goals Achieved

- Observing surface and near-surface conditions along the length of disposal cell or trench
- Determining whether the monitored conditions at one portion of a disposal or containment cell may be changing significantly versus another portion

An advantage of this strategy is that soil water conditions are monitored along a potentially long horizontal transect. The monitoring trenches could be constructed, for example, to parallel the entire length of a disposal unit. This allows site personnel to study changes in the near-surface soil water balance either adjacent to or above the waste material. The water holding capacity, considered important for assessing the potential for downward flow of water (Gee et al., 1998), can be monitored appropriately and calculated. If data from the trenches indicate that large volumes of water are percolating below the root or evaporative zones, then it is reasonable to assume that leachate has been generated, and that some type of corrective action should be taken. Another advantage of the trench concept is that spatial variability of soil hydraulic properties and soil water conditions can be assessed. Understanding the spatial variability of these properties allows site personnel to assess the significance of local changes in water content.

It is important to note, however, that the trench strategy is very depth-limited. From a practical standpoint, the trench cannot be excavated too deeply because of health and safety requirements to protect site personnel which increases costs; moreover, it would increase the likelihood of wall collapse, thereby affecting the continuity of the soil material and water flow. With this restriction in mind, the trench strategy is useful for monitoring near-surface conditions, limiting its functionality as a monitoring strategy. In arid and semi-arid regions, where vadose zones are 10s to 100s of meters thick, instruments installed in a trench may not be capable of providing direct information on releases to the subsurface. However, if the trench is used in combination with other strategies, then it can provide important early-time information on possible downward movement of water.

### 3.2.2 Monitoring Islands Strategy

Goals Achieved

- Hydraulic gradient can be determined, improving flux calculations
- Improves understanding of water flow throughout the soil profile
- Soil and/or pore water in the disposal zone can be sampled

An advantage of the monitoring island strategy is that instruments can be installed at different depths and at different directions from the center of the island (e.g., instruments can be installed radially, like spokes on a wheel). This allows much higher depth resolution for quantifying deep percolation of water below the root and evaporative zones. At the Maricopa site, instruments were installed to 3 m depth, so that we were able to monitor the zone where most of the rapid changes occurred. Depending on the needs of the monitoring program, the islands can be installed much deeper and with larger diameter material, increasing the capacity of the strategy for monitoring near-surface and deeper subsurface conditions. The islands can be installed relatively close to one another. At the Maricopa site, we installed two islands 5 m apart, with reasonable confidence that the islands were independently monitoring subsurface conditions. Furthermore, the islands can be secured so that expensive equipment is stored safely. In remote areas, or at sites where security is a primary concern, this could be a distinct advantage.

Though the monitoring islands represent a very flexible strategy, they provide poor spatial coverage of soil water conditions. Thus, multiple islands will be needed if they are used as the primary strategy for any monitoring program, which increases costs and complexity. This may be particularly important if the monitoring instruments are remotely queried, and if the data loggers are independently operated. We believe that the island strategy would be most beneficial to a monitoring program when used in combination with one or two other strategies, such as the borehole or trench strategy. This would allow intensive measurements to be taken at a few, key locations and less intensive measurements elsewhere.

### 3.2.3 Borehole Monitoring Strategy

Goals Achieved

- Deep unsaturated zone monitoring using different instruments
- Simultaneous monitoring of saturated and unsaturated material
- Enhanced ability to make redundant measurements in same borehole

An advantage of the borehole monitoring strategy is that new monitoring locations can be added to the program relatively easily, thereby allowing the program to expand as necessary. By contrast, adding a new monitoring trench is much more difficult or may not be possible depending on site geometry. Boreholes can be advanced directly below disposal zones using angled or horizontal drilling rigs, which are now commonly used and accessible. This allows the site personnel to design a monitoring program which focuses on measurements taken to confirm or disprove the release of contaminants or leachate material from the disposal cell, rather than on measuring ambient conditions adjacent to the cell. Once the borehole is drilled, instrument clusters can be added that include tensiometers and solution samplers. Boreholes completed as access tubes create ports that can be used for neutron probes, or other instruments that are developed in the future and that can be lowered into or pulled through the tube. During the field experiments at the Maricopa site, we studied the use of EM-39 and crosshole radar methods. Though insufficient data were available to be included in this report, initial data analyses indicated some promise, especially with the EM-39 method. Other methods that become available could be used in the access tubes.

The borehole monitoring strategy suffers from a number of disadvantages. A limited number of instruments can be installed in any single borehole, and the integrity of any low-conductivity layer between sampling points is difficult to confirm. For this reason, we chose to install only a single device in each borehole, then backfill to the surface. This increased the drilling cost, and the number of potential pathways for focused flow. Another potential disadvantage is that the loss of a single borehole could result in the loss of numerous monitoring points, especially if the borehole is completed as an access tube. If the monitoring program relies solely on the borehole monitoring strategy, then the loss of a few access tubes could leave large gaps of the subsurface unmonitored. New access tubes can be installed as replacements; however, it is sometimes difficult to transfer time series data of water content readings from one borehole to another. Uncertainty in the transferred readings can be difficult to explain without a sufficiently long time series of data.

### 3.2.4 Geophysical Monitoring Strategy

The geophysical monitoring strategy has a unique advantage over the other strategies in that some of the techniques are non-intrusive and others are intrusive. The non-intrusive instruments (EM-31 and EM-38) are very portable, allowing the user to collect information over a large area which otherwise would not be possible. Data collection is very rapid and facilitated by using a portable data logger. The portability of the instruments allows users to collect data over wide areas in a very short amount of time. It appears that the data can be correlated with some confidence to soil water content, indicating that non-intrusive measurements can be used for monitoring subsurface changes in water content (Kachanoski et al., 1988). Data collected from the Maricopa project support this conclusion (Young et al., 1997), but more research needs to be done to understand the limitations of the method. The data can be analyzed using time invariance (Vachaud et al., 1985), so that only specific, time-invariant locations at the site are measured, potentially reducing personnel effort and cost.

The intrusive, ERT method can provide data at multiple depths and locations adjacent to those used for borehole monitoring. The field design used at the Maricopa site consisted of 12 boreholes at 10 m lateral spacing, with conductors at 1 m depth offsets. Resolution was approximately 0.5 m, which is too low for detecting preferential flow pathways, but clearly high enough for monitoring field-scale water movement. The boreholes were advanced to 15 m depth. The water table was clearly identified at 11.5 m, as were several electrically distinct layers across the site. We showed very clearly during Experiment 1 that wetting fronts were detectable using the ERT method, and that the results could be confirmed using the neutron probe method. Extensive data analysis can yield 3-dimensional tomograms, provided that the borehole spacing is designed appropriately. However, we did not have sufficient data to quantify the lower detection limit of water content change at the scale used during the field experiments, so the use of this technique in soil with low water holding capacity could not be verified.

Some disadvantages of the geophysical strategy were identified. First, the EM technique is sensitive to external electrical noise, especially in the presence of AC or DC power or other metallic objects (e.g., electric fence, steel highway culvert). A significant number of monitoring points inside the irrigated plot were removed from the data base because they were influenced by shallow electrical lines that were installed on the field plot. Industrial areas could also be affected by either power lines or metallic objects. Second, the geophysical techniques provide volume-averaged data. It is therefore very difficult to identify small-scale spatial variability in water content or water movement, especially at depth. The response functions for each device are different depending on orientation (see McNeill, 1992); thus, isolating specific depths is complex and still a subject of research (Borchers et al., 1997). Third, changes to EC could be indicative of changes in either water content, salinity, or both. However, using the EM technique to measure soil water content, by itself, could be difficult without a significant amount of on-site calibration and ground-truthing.

## 3.3 Strengths and Weaknesses with Respect to Installation, Maintenance and Replacement

The strategies emphasized during this research have specific characteristics that either help or hinder their use in long-term monitoring programs. Because the goals of monitoring programs may change over time, the direction and emphasis of the program needs to be adaptable. This section provides a list of strengths and weaknesses of each strategy with respect to installation, maintenance and replacement. The focus of this section is on the individual monitoring systems that support the strategies, rather than the strategy itself. The list stems from experience obtained during the field experiments at the Maricopa site. Technical personnel at other sites may have different experiences.

### 3.3.1 Monitoring Trench Strategy

#### 3.3.1.1 Installation

Strengths

- Multiple instruments can be installed at the same location

Monitoring clusters enhance the redundant measurements of performance measures. The use of tensiometers and HDS units permits direct comparisons of two instruments that measure different soil water conditions, but the same performance measure.

- Completion of access ports is visible

Directly observing the backfilling and sealing of the access ports increases the confidence that preferential flow pathways are not created during the installation of monitoring instruments.

- Single manifolds can be used for many solution samplers

Multiple soil solution samples can be obtained simultaneously, reducing personnel costs.

- Horizontal neutron probe tubes can be installed when the trench is open

The horizontal access tube can be used for collecting large amounts of data at very small lateral offsets. The installation procedure is simple and the presence of the access tube could be very useful as new instruments become available for field monitoring.

Weaknesses

- Excavation disrupts the soil surface and trench walls

This makes installation of instruments at specific distances from the trench wall very difficult. Extra care can be used during excavation to ensure that the trench walls are smooth, but this may not be possible in field situations.

- Replacing material to natural bulk density and layering is very difficult

If the trench is backfilled (as done during this research), the material should be replaced to approximately the same layering and bulk density. Large differences between undisturbed and disturbed materials could affect water movement and the representativeness of the instrument readings near the trench wall.

- Wire lengths for the electronic instruments have the potential to be very long

Long lead lengths can introduce higher errors in measurements because of residual voltages and temperature affects. This can be reduced by using low resistance (higher gauge) leads or burying the wires deeper in the soil profile to reduce diurnal fluctuations.

- Adding more samplers to the monitoring clusters is difficult after trench is closed

Closure of the trench removes accessibility to the undisturbed soil, which is both an advantage and disadvantage of the trench strategy. It is an advantage because it provides physical protection to the instruments, but a disadvantage because it limits the flexibility of the strategy to expand the number of instruments for future monitoring.

### 3.3.1.2 Maintenance

Strengths

- Headspace on tensiometers is easy to access

Measurement of the headspace and recharging of tensiometers are required for use of these instruments. Tensiometers used at Maricopa were protected by irrigation valve boxes, but a more water-tight design should be used for better protection.

- Most instruments in the trench are protected from the elements

Temperature fluctuations, which affect many instruments, are minimized because of the depth of burial and thickness of soil. The tensiometer headspace was (in our case) the only exposed instrument. Data from the site improved the theoretical framework for temperature corrections of tensiometers (see Section 4.3 below and Warrick et al., 1998a).

Weaknesses

- Instruments cannot be easily removed for calibration or maintenance

Removal of the instruments will result in disruption of the trench backfill or surface soil material, possibly affecting the representativeness of measurements.

- Electrical connections are below ground

The most significant cause of instrument failure at the Maricopa site was corrosion of electrical connection between sensors and wire leads. Because these are completed below or at ground surface, special care must be taken to ensure that all connections are fully weatherproofed.

#### 3.3.1.3 Replacement

Strengths

- Electrical connections can be made accessible for replacement

The trench can be designed so that electrical connections are accessible and replaceable. Monitoring instruments must be designed, however, so that potted leads reach ground surface before the first electrical connection.

- Pressure transducers on the tensiometers can be easily replaced

Of the instruments used in the trench during the Maricopa experiments, only the tensiometers required this secondary measurement component. Pressure transducers, designed to be located near ground surface, were replaced on all tensiometers at the trench before Experiment 2 with little difficulty.

Weaknesses

- Intrusive activity needed for instrument replacement

As stated above, the instruments can not be replaced without disruption of the surface material. During the field experiments, several instruments failed to provide reliable data or samples, and were taken off line, resulting in data gaps. Replacement would have been beneficial to the experiments.

- Fully decommissioning the trench would be very difficult

Removing all instruments, including the conduit, wires and cables, will be extremely difficult without fully excavating the trench area. If the trench were installed either in or adjacent to engineered cover materials, then disruption of the barrier system could occur, increasing the risk for recharge to occur.

- Rewiring could be problematic if new instruments are added

New conduit was required before Experiment 2 to store wire leads used for replacement pressure transducers. Depending on the size of the conduit and the wire bundles used during initial field installation, existing conduits could be sufficient, making installation and security of new conduit unnecessary.

### 3.3.2 Monitoring Islands Strategy

#### 3.3.2.1 Installation

Strengths

- Islands can act as hubs for monitoring systems

The island is a centralized area for electronic and other support equipment. The need for electrical conduits and other storage equipment are greatly reduced because components are stored in a central location.

- Easy to incorporate redundancy of measurements

As stated above, we advocate the concept of collecting data from instruments that reduce to one or two performance measures. The monitoring islands encourage the installation of multiple instruments in close proximity to one another, so that side-by-side comparisons can be made easily. This strength makes the island strategy more adaptable to changing priorities of the monitoring program.

- New instruments can be added at different depths and through additional ports with little difficulty

Before the start of Experiment 1, six sampling ports each were added to the monitoring islands in less than one day. The ability to easily increase monitoring capabilities greatly enhances the flexibility of the system when monitoring goals are modified.

- Instruments can be installed at any orientation through the island wall

Monitoring instruments at the Maricopa site were oriented parallel to the X and Y axes of the site coordinates. At other sites (e.g., Scanlon et al., 1997), instruments were oriented normal to the island wall. This flexibility improves the targeting of specific layers (either natural or engineered) adjacent to the island.

- Islands can be installed into deep soil material

Boreholes were drilled to approximately 3 m depth at the Maricopa site, though the drilling rig used was capable of advancing deeper than 20 m. Deeper monitoring can be beneficial to monitoring systems in arid and semi-arid environments, where vadose zones are often thicker.

- Wiring remains inside the island

As stated above, corrosion of wiring and connections was a significant cause of data loss from devices in the monitoring trench. We found no corrosion in the islands during the field work, because no direct contact existed between soil and wiring and because the relative humidity was lower, with condensation of water reduced to nearly zero. The accessibility of the wiring permits easier expansion when new instruments are installed.

- Subsurface material is accessible

The immediate proximity of the island to undisturbed subsurface material permits sampling for future textural or chemical analyses, or both. This greatly simplifies the sampling procedures if small amounts of material are collected at infrequent time intervals, because surface disturbance is obviated.

- Easy to make manifolds for multiple solution samplers

The close proximity of the solution samplers (in contrast to those in the monitoring trench) facilitates the installation of a central manifold for collecting numerous samples simultaneously. This reduces staff cost by quickening the sampling process.

Weaknesses

- Requires intrusive activity with less common rig equipment

Installation of the monitoring island culvert into undisturbed soil is intrusive, and therefore requires the presence of drilling equipment. Therefore, obvious limitations exist for installation of monitoring islands after closure of the disposal cell. In some cases where the island culvert is backfilled within the engineered barrier or disposal area, this weakness becomes insignificant because drilling is unnecessary.

- Backfilling the annular space is difficult

Some difficulty was encountered during backfilling of the annular space between the borehole wall and the outside of the culvert material. The problems stemmed from what, we believe, was a slight expansion of the soil material into the borehole, reducing the effective borehole diameter. During the backfilling process, we noticed that the sieved material tended to bridge, and that the bulk density was probably not consistent with the undisturbed material. (Bridging occurs when one or two large particles of backfill become lodged in the annular space, causing finer grained material to pile up behind it. This can cause potentially large gaps in the annular space to be unfilled.) The experimental results indicated, however, that water flow through the annular space was similar to that recorded in the undisturbed soil, but that the dispersivity tended to be higher in the annular material.

- Presence of metal close to soil material could affect TDR or surface EM readings

Islands made of metallic material could influence the readings of TDR and EM systems. Several EM data points were removed from the data base because the instrument was affected by the monitoring island. The use of concrete or fiberglass material could reduce this problem.

- Instruments need to be installed within a meter of the island wall

The diameter of the monitoring island poses a practical and physical limitation with respect to the distance that instruments can be installed away from the island wall. This is because the augers or drills, used to create the access port, should be no longer than the diameter of the island. Therefore, the islands are restricted to relatively localized measurements, except where installation can be done in sections, which are no longer than the monitoring island diameter.

#### 3.3.2.2 Maintenance

Strengths

- Individual instruments can be removed and maintained

Unlike permanently-installed instruments that support other strategies, those installed in monitoring islands are relatively accessible and can be removed for maintenance and calibration. This was helpful during the interim period between Experiments 1 and 2, when a number of tensiometers were removed and pressure tested. Other types of routine maintenance are simplified because of the easy access to instruments.

- Components are protected from the sun

Direct exposure to the sun, especially in the desert southwest, led to some heat-related problems during the field experiments. For example, the high heat caused a deep-cell marine battery, used to operate the multiplexer for the Dynamax TDR system, to lose its charge more quickly than normal. This required the installation of a backup battery charger to maintain adequate charge. Also, temperature fluctuations inside the truck boxes that stored the data loggers, caused significant diurnal fluctuations to develop in the HDS units. Protection from the sun inside the monitoring island reduces these impacts and related extra maintenance.

- Connections less likely to corrode

As stated above, the lack of direct contact with either the outside environment or soil material and the lower humidity and subsequent lack of significant condensation of water eliminated corrosion of soldered connections at the site. In the long term, this greatly reduces the maintenance costs at the site.

Weaknesses

- Metal island themselves are susceptible to corrosion

Long-term monitoring programs that use metallic islands may be affected by corrosion of the island material itself. If the island strategy is utilized for relatively short-term programs (e.g., 5 - 10 years), then this may not become a significant issue. However, monitoring programs that last for decades or longer probably should rely on different culvert material, such as fiberglass or concrete.

#### 3.3.2.3 Replacement

Strengths

- Instruments and samplers can be more easily replaced

As implied above, instruments and associated wiring can be replaced relatively easily because of their close proximity to the sampling port.

Weaknesses

- The island material itself cannot be easily replaced

It would not be practical or feasible to replace the entire monitoring island, should it become damaged and unsafe. Therefore, an entire new facility would need to be constructed, which could adversely impact engineered cover material or the surrounding area. Similar to restrictions on the monitoring trench strategy, design personnel should consider installing monitoring islands before site closure.

### 3.3.3 Borehole Monitoring Strategy

#### 3.3.3.1 Installation

Strengths

- Technology for installing monitoring points is readily available

Methods of drilling monitoring points have been used for,in some cases, thousands of years (Driscoll, 1986). Newer methods (e.g., cone penetrometer method ) can also be used depending on the purpose of the borehole.

- Subsurface material can be sampled continuously during drilling

Site characterization activities are greatly enhanced by sampling subsurface material. For thick vadose zones, installation of borehole monitoring points is the only option available for characterizing soil/rock layering and other properties. Though the ability to collect "undisturbed" samples at depth is questionable, the material can be placed fairly well within the geologic framework.

- Borings can be completed below grade

Security against accidental or intentional damage to boreholes may sometime require completion below grade. The borehole monitoring strategy can be implemented so that completed points, including cables and wires, are secured behind locked caps.

- Alternative material is available for access tubes

A wide variety of material is available for access tubes, including PVC, stainless steel, and ABS. This flexibility permits the designer to specifically choose access tube construction for the intended usage.

Weaknesses

- Instruments cannot always be placed precisely in deep boreholes

Placement of monitoring points inside deep boreholes can be affected by potential cave-in, rocks or other protrusions. Moreover, deep boreholes may not be perfectly vertical, causing the monitoring point or access tube to vary from the final designed location.

- Lateral distances between boreholes can be quite far

Some boreholes used for deep tensiometers were almost 60 m from the data logger. The long wiring needed for these locations could lead to some measurement error.

- Incomplete backfilling of boreholes may lead to conduits for water flow and contaminant transport

Of the more than 100 boreholes constructed to support site experiments, only three were completed with grout, sand, and bentonite. The annular space (between 2.05 and 3.22 cm) of the other boreholes were backfilled to ground surface with sieved native material. Special care was taken to avoid bridging in the annular space. However, it is difficult to ensure that the boreholes themselves are not conduits for rapid downward water movement.

- Large diameter boreholes could be susceptible to higher measurement interference

The neutron probe is affected by the material immediately outside of the access tube; larger diameter boreholes mean that the neutron probe is more affected by the backfill material than smaller diameter holes. It is therefore important to consider the counter issues of wanting a small borehole to reduce the influence of backfill material on measurements, but needing a larger diameter borehole to facilitate backfilling.

- Installation of boreholes can drag down contaminants from shallow to deeper depths

It is possible that contaminants can be dragged downward from shallow soils to deeper, uncontaminated soils. This increases the possibility of cross-contamination, and thus, false positive readings.

#### 3.3.3.2 Maintenance

Strengths

- Portable instruments (i.e., neutron probe) can be removed from the site

From a strictly instrumentation standpoint, portable instruments that are pulled through the access tubes can be brought back to a laboratory for calibration and repair without altering or affecting the access tube in any way. Other instruments, such as the deep tensiometers, can be easily disassembled, so that the pressure transducers can be returned to the lab for calibration. Other system components, such as the vacuum system for collecting solution samples, can also be brought to the site or removed at the discretion of the field personnel.

- Access tubes have no electronics or moving parts

The access tubes generally require little to no maintenance. However, we noticed that water condensation appeared on the walls of the access tube during Experiment 1 and affected the neutron probe readings; so, we used Drierite® to maintain dryness in the access tube. We also noticed that a small number of o-rings, used to seal sections of the access tubes, became brittle from exposure to the sun, so these were replaced as needed.

Weaknesses

- Some instruments, which are permanently left in the boreholes (i.e., deep tensiometers and solution samplers), cannot be maintained easily

During the field experiments, one-way check valves became stuck, making it difficult for the sampler to maintain an adequate vacuum for collection of samples. By pressurizing and depressurizing the sampler, we were able to fix the problem and continue sampling. However, if this "repair" failed, then the sampler would have been disabled. Several deep tensiometers provided suspect data because of difficulty in sealing the rubber stopper to the tensiometer cup. The lack of adequate sealing was manifested in erroneously low water tension values. In several cases, we were unable to repair the tensiometer cup, leading to removal of the tensiometer from the sampling program. Long-term monitoring programs that rely on these instruments could also be affected.

- Borehole maintenance can be difficult as the boreholes become deeper

Deeper boreholes used for neutron probe access tubes (e.g., > 5 m) cannot be readily maintained if they become either wet, or if the integrity of individual borehole sections is lost. Thus, water leaking through these poorly sealed joints (between borehole pipe sections) could lead to abandonment as well.

#### 3.3.3.3 Replacement

Strengths

- Portable instruments can be replaced easily

Measurement instruments that are taken to the site and found to be faulty can be brought back to the laboratory and replaced. This would apply to the neutron meter, which failed several times during Experiment 1, and to the pressure transducers used on the deep tensiometers.

Weaknesses

- Borehole replacement requires redrilling

Depending on the location of the original borehole, and the proximity to engineered cover material, replacement may not be an option. Loss of one or more of these sampling units could therefore greatly affect the ability of the monitoring program to detect potential releases from the disposal area. The cost of drilling new boreholes must be incorporated in the operational and maintenance budgets.

- Stationary instruments probably cannot be replaced in same borehole

Several of the boreholes at the Maricopa site were equipped with instruments that cannot be replaced, including the ERT boreholes, tensiometers and solution samplers. Loss of instruments in these boreholes from the sampling grid led to data loss during the experiments. Long-term monitoring programs likewise would be affected by the loss of these boreholes. Though replacement through additional drilling can be done, it is difficult to transfer the new data to the older time series, adding some uncertainty to the observations.

### 3.3.4 Geophysical Monitoring Strategy

#### 3.3.4.1 Installation

Strengths

- Surface EM instruments are not permanently installed

No permanent installations are needed for the EM readings; rather, only surveyed monitoring points are required. During the site experiments, a total of 90 surveyed points were chosen around and inside the irrigated plot, providing a set of spatially distributed data. Therefore, no security measures needed to be taken to protect on-site equipment, other than markers used for future measurement points.

- EM-39 can be used in the same boreholes as monitoring wells and neutron probes

The EM-39 instrument, tested on a limited basis during Experiment 1, can be used in the neutron probe access tubes. [The data looked promising, but were not sufficient to describe in these research documents.] No special installation procedures were needed. The EM-39 is an example of a cross-over instrument that can support the borehole monitoring and geophysical monitoring strategies.

- ERT monitoring points are permanently installed at the site

Each of the 12 ERT monitoring points were permanently installed at the site. Though this represents a disadvantage with respect to maintenance or replacement, it provides data from a stationary point in space, thereby removing potential errors due to poor placement of portable EM instruments.

- ERT data acquisition systems can be designed for portability

The data acquisition system used for collecting tomography data was contained in a small trailer and removed from the site during down times. The portability of this electronic equipment thus represents an advantage of the method, because no specific actions need to be taken to secure or otherwise maintain the equipment at the site.

Weaknesses

- Duplicating exact placement of the EM instruments is difficult over time

Because each data point collected with the EM instruments required the unit to be (in our case) placed on the ground surface, a potential exists for the instrument to be incorrectly located, producing biased data. This potential problem was minimized during the site experiments by assigning specific personnel to EM data collection. However, long-term monitoring programs will need to emphasize accurate instrument placement to ensure accuracy of data.

- Some techniques may not work properly under all soil conditions

Highly conductive subsurface materials reduce the effectiveness of EM instruments because of higher attenuation of electromagnetic waves. We attempted to use the downhole ground-penetrating radar technique for obtaining 2-D tomograms. However, the 10 m lateral offset between access tubes was too wide, so the technique could not be used. Though surface GPR has been used for monitoring soil water content (e.g., van Overmeeren et al., 1997), the downhole method is new and still under development.

- ERT requires substantial lengths of wiring when boreholes are far apart

The ERT design used at the Maricopa site required 15-wire cable from each of the 12 boreholes, all of which were connected to a central processing unit immediately off the irrigated plot. If the depth of measurement is at least 1.5 times the lateral offset of the couplets, as designed here, monitoring large facilities would require potentially very deep boreholes and long lead lengths. This leads to a more complicated monitoring system and hence higher installation costs.

### 3.3.4.2 Maintenance

Strengths

- Portable EM instruments can be removed from the field for servicing

Instruments can be maintained more easily in a laboratory setting. Maintenance of data acquisition equipment used for ERT can be maintained more easily because of its portability.

Weaknesses

- Portable instruments could provide different readings with time if maintenance or calibration procedures are not performed properly

For example, data collected from the EM instruments required periodic zeroing and rechecking to ensure a minimum of drifting. Though standard operating procedures are available, different persons will carry out these procedures to different degrees, thereby leading to possible measurement biases.

- ERT wiring is permanently left in the borehole

Maintenance of ERT wiring, sources and conductors is not an option, using the design implemented at the Maricopa site. Therefore, no actions can be taken to repair or refurbish downhole components of the system, making it more vulnerable to degradation during long-term monitoring programs.

### 3.3.4.3 Replacement

Strengths

- Portable geophysical instruments can be replaced easily and taken back to the site

This permits instrument replacement or upgrades as new products become available.

Weaknesses

- ERT sources and detectors cannot be replaced without redrilling

Given the specific geometrical requirements of the ERT method, long-term monitoring programs could become greatly affected if even one borehole is damaged. Therefore, it may be appropriate to use ERT methods in combination with other strategies, so that long-term monitoring programs do not rely specifically on vulnerable monitoring systems.

# 4 DISCUSSION

## 4.1 Use of Strategies to Fulfill Subgoals

Subsurface monitoring (Section 2.3 above) is composed of a number of subgoals. The monitoring strategies that we discuss, when used together, provide assurances that the goals of the monitoring program are achievable. However, because the strategies emphasize the monitoring of specific subsurface zones (e.g., deep or shallow soil), some of the subgoals may be poorly addressed using only one or two strategies. Table 4.1-1 provides a list of 11 subgoals of subsurface monitoring, based loosely on the three major goals for monitoring programs (Section 2.3). Check marks placed in the adjacent columns indicate whether a specific monitoring strategy is reasonably capable of satisfying that specific subgoal. The bullets listed below provide an explanation of why some strategies are better than others.

- Collect sufficient data over a time period long enough to quantify background variability

Quantification of environmental impacts is necessarily based on changes from baseline conditions. Whether the preoperational monitoring phase is used for establishing baseline conditions, or whether the monitoring program is maintained continuously from preoperational through postoperational phases, baseline conditions must be quantified. This reduces potential occurrences of false negatives (data incorrectly indicate that no change from baseline has occurred) as well as false positives (data incorrectly indicate significant change has occurred). Seasonality, background trends, natural variability should be observable using each of the monitoring systems. A variety of parametric and nonparametric statistical tests are used for establishing baseline conditions (see, for example, Gilbert, 1987). The baseline conditions include estimates of mean, inherent (or random) variability, seasonality, and long-term trends. Failure to understand each of these aspects of time-varying data sets can lead to false positive and false negative conclusions when compared to future data sets. All four strategies are checked off because baseline environmental conditions can be quantified using each of the strategies.

- Establish surface/near-surface conditions and determine spatial variability along the length of a disposal unit or trench.

Near-surface water storage has been considered an important parameter for understanding when infiltrating water breaks through engineered layers (Gee et al., 1998). If we use the premise that water entering a disposal facility from the surface is the predominant source of potential leachate, then monitoring changes in water content below or adjacent to the disposal area can be used to indicate the possibility of contaminant movement. Enhanced monitoring of near-surface soil or cover material could thus be an important task for providing early warning of potential releases. The need for near continuous measurements along a trench around or above disposal facilities is directly addressed using the monitoring trench strategy, especially with the use of horizontal neutron probe access tubes. Likewise, the ease with which EM-31 and EM-38 data can be collected, some recent successes with the strategy (Scanlon, et al., 1999), and the non-destructive nature of the method makes it also well suited for this purpose.

- Establish hydraulic gradient in both shallow and deeper soils

The direction of the hydraulic gradient is, ultimately, one of the most important factors that govern potential water movement into or out of disposal area. A lack of monitoring devices installed in vertical transects at disposal sites, makes the direction and magnitude of the hydraulic gradient difficult, if not impossible, to determine. Therefore, provisions need to be made for monitoring subsurface environments vertically, as well as horizontally. Considering the restrictions on excavation for monitoring trenches, the MT strategy may not be adequate by itself for site monitoring. Geophysical monitoring likely will not provide accurate assessments of hydraulic gradients either, though research is still ongoing. However, the use of borehole monitoring, especially with the recent advances of borehole tensiometry and the use of heat dissipation sensors, greatly improves the ability to measure soil water tension in deep or shallow environments. We found that the monitoring islands provided excellent access to deeper soils

Table 4.1-1. Breakdown of adequacy of monitoring strategies to fulfill subgoals. MT, MI, BM, GM correspond to monitoring trench, monitoring island, borehole monitoring and geophysical monitoring, respectively. Check marks denote adequacy.

| **Subgoal** | MT | MI | BM | GM |
|---|---|---|---|---|
| Collect sufficient data over a long-enough time period to quantify background variability | ✓ | ✓ | ✓ | ✓ |
| Establish surface/near-surface conditions along the length of a disposal unit or trench | ✓ |  |  | ✓ |
| Establish hydraulic gradient in both shallow and deeper soils |  | ✓ | ✓ |  |
| Quantify flux into and/or out of the disposal area |  | ✓ | ✓ |  |
| Collect sufficient quantities of reliable data to enable comparisons with baseline conditions | ✓ | ✓ | ✓ | ✓ |
| Monitor deep soil conditions with both direct and indirect instruments |  |  | ✓ | ✓ |
| Quantify uncertainty in measurements and observations | ✓ | ✓ | ✓ | ✓ |
| Monitor water table for both water level and water quality |  |  | ✓ |  |
| Ensure that decommissioned monitoring systems do not affect the integrity of the containment unit | ✓ | ✓ | ✓ |  |
| Emphasize consistency of data collection throughout different phases of monitoring programs | ✓ | ✓ | ✓ | ✓ |
| Include non-intrusive activities during latter phases of the monitoring programs |  |  | ✓ | ✓ |
| Consider the potential for retrofitting existing ports to accommodate new instruments |  | ✓ | ✓ |  |

(3 m in our case), improving the determination of gradients. Therefore, if the facility is located in an area with a deep water table, and if the licensee includes goals of monitoring deep and shallow conditions, then using devices in islands and boreholes could provide the necessary data.

- Quantify flux into and/or out of the disposal area

Combining the previous two items (water storage and hydraulic gradient) permits the quantification of flux. The ability of the monitoring island and borehole monitoring strategies to facilitate the collection of soil water content and tension data in deep or shallow profiles make them well suited when flux calculations are needed. Monitoring trenches alone, though excellent for determining spatial variability of conditions along a long transect, are not well suited for measuring hydraulic gradients. The geophysical monitoring strategy (as used during this research project) relied on the collection of electrical conductivity and resistivity, which cannot be converted to soil water tension without the use of soil water retention curves; thus, this strategy would not be well suited either. This strategy would not be appropriate either.

- Collect sufficient quantities of reliable data to enable comparisons with baseline conditions

This goal obviously applies to all strategies. Without sufficient amounts of data, either spatially or temporally, it is not statistically possible to conclude whether baseline conditions have changed. Therefore, all monitoring strategies incorporated into a site monitoring program need to be used long enough to allow comparisons to baseline conditions. If baseline conditions are not established, then findings with respect to environmental impacts are ambiguous. Moreover, if sufficient data are not available for comparisons with baseline conditions, then findings also cannot be made. For example, if the user seeks to know the minimum number of data points needed for running comparisons on serially-correlated data, then he/she will need to have an acceptable autocorrelation coefficient and accuracy known *a priori*, and a known lag distance in time (see Gilbert, 1987, esp. Eqn. 4.20). This could require several dozen data points depending on the accuracy needed for the comparison. If the data are collected monthly, then several years of data might be needed; if data are collected quarterly, then required data collection could be longer.

- Monitor deep soil conditions with both direct and indirect instruments

Deep soil profiles, located in arid and semi-arid environments can be up to several hundred meters thick. Depth of excavation would be an obvious limitation for the monitoring trench and island strategies under these circumstances. Surface geophysical techniques also would not be very effective, because they provide depth-averaged values of resistivity in relatively shallow soil. The ERT method, however, showed significant promise, especially when the soil profile was initially dry as before Experiment 1. Borehole monitoring, with the advancement of tensiometry and solution samplers (both dual-chamber or improved single-chamber models), were found to be very effective at monitoring changes in pore water pressure and concentration, respectively. Therefore, borehole monitoring will likely be the optimum strategy for sites located in arid and semi-arid climates, especially if the monitoring program emphasizes water movement in deep soil at several depths below the disposal area.

- Quantify uncertainty in measurements and observations

Quantifying uncertainty in measurements and observations at the disposal facility is particularly important when predicting groundwater or soil water concentrations. *In-situ* measurements of soil water conditions, and *ex-situ* characterization of soil hydraulic and transport properties needs to be sufficient so that 1) uncertainty analysis on the data themselves can be performed, and 2) modeling water flow and solute transport through the vadose zone can be accomplished with uncertainty analysis. Recent publications stress the need for including probability distributions in flow and transport modeling (Meyer et al., 1997). Therefore, because the measurements themselves are often used as input for inverse modeling, or as calibration data for the modeled parameter estimates, probability distributions of the data (e.g, characteristics of the distribution – mean, standard deviation, etc. – should be quantified for specific locations). This subgoal is related to others listed here, but is considered important enough for specific mention.

- Monitor water table for both water level and water quality

Many environmental regulations either mandate or emphasize monitoring of groundwater quality for quantifying environmental impacts. We include this subgoal here for that reason. Historically, the borehole monitoring strategy has been the only viable alternative available for monitoring water table depth and ground water quality, especially in deep water table environments. We found that ERT worked very well for identifying the position of the water table, but we did not use it for monitoring water quality. If the monitoring program emphasizes groundwater monitoring and if the water table is very shallow, monitoring islands could be used to complement the use of boreholes. Surface geophysical monitoring would probably not be an accurate strategy for looking at groundwater quality, though research is still being done on this subject.

- Ensure that decommissioned monitoring systems do not affect the integrity of the containment unit

Decommissioning of monitoring systems can affect the integrity of engineered barriers, creating fast flow paths toward the waste material. Care should be taken with decommissioning monitoring systems used to support the trench and island strategies, because of the large amounts of electrical wire and multiple exit/entry ports that are generally used. Attempts to fully decommission the monitoring trenches at the Maricopa site, for example, will require re-excavation of the backfill material. Depending on the proximity of a buried trench with respect to the waste material at a true disposal site, re-excavation could become a significant issue. Therefore, if the monitoring program calls out for the use of monitoring trenches and monitoring islands, during the preoperational and operational phases, with subsequent decommissioning of these features, special precautions would need to be taken to ensure that engineered barrier systems are unaffected. Boreholes have traditionally been decommissioned using cement grout, so use of this strategy in the overall monitoring program could be advantageous in site characterization through operational phases, if postoperational monitoring is minor. It may be possible to use traditional methods of decommissioning ERT boreholes, depending on the method of installation; however, the more commonly used non-intrusive methods require no decommissioning, so this method was not checked in the table.

- Emphasize consistency of data collection throughout different phases of monitoring programs

Regardless of the monitoring strategy, it is important to emphasize consistency of data collection throughout the monitoring program. This includes using similar time intervals, monitoring locations and sensor types across each distinct monitoring phase. Site characterization programs implemented before licensing should be maintained during preoperational programs, thereby providing longer time series and higher confidence in the data. Decommissioning monitoring devices or access tubes after site characterization ends, and then implementing a different operational monitoring program does not necessarily improve the quality of the data set, because most of the temporal variations need to be requantified. Monitoring plans should indicate how the monitoring strategies will be maintained when the facility closes, when the program shifts from operational to postoperational phases.

- Include non-intrusive activities during latter phases of the monitoring programs

Non-intrusive activities refer specifically to surface geophysical techniques, including EM-31 and EM-38, as used during this research project. Ground-penetrating radar, not used during the Maricopa experiments, has been shown to improve site characterization (Kung and Lu, 1993) and subsurface monitoring (van Overmeeren et al., 1997; Hubbard et al., 1990), though the soil texture and presence of strong lateral discontinuities in the soil horizons will affect the depth of penetration of the radar waves. Other methods that require intrusive activities, especially if this involves potential borehole drilling or excavation, could cause more problems than they solve. Breaching the engineered barrier during post-closure time periods, when it exists in some level of static equilibrium, could create fast flow paths or enhance erosion or settlement rates. However, boreholes that are installed prior to postoperational periods, or those installed so as to avoid potential damage to the disposal area, can serve as access ports for the insertion of portable instruments, such as neutron probes. Though the boreholes are clearly intrusive by nature, they require low maintenance by themselves and allow data to be collected without any site disturbance. Given that the geophysical monitoring strategy includes monitoring devices which are non-intrusive, we opted to reject the use of the MT and MI *strategies and include the BM strategy for those situations* where non-intrusive monitoring is required.

- Consider the potential for retrofitting existing ports to accommodate new instruments

The monitoring island and borehole monitoring strategies use access ports which can be retrofitted to accommodate new instruments as they are developed. The neutron probe access tubes should be resilient against environmental damage, and the monitoring islands should be made of material that is equally resilient (e.g., fiberglass). For example, downhole ground-penetrating radar is currently being tested for monitoring changes in water content, much in the same way as ERT (Eppstein and Dougherty, 1997). Other technologies that rely on non-stationary probes could be developed in the future and found promising. The existence of access tubes and ports will facilitate the use of these new technologies. Installing new devices through access tubes at the backfilled trench, as used during the Maricopa experiments, would be difficult, unless the horizontal access tube was used. Likewise, access tubes were not used for the majority of monitoring activities in the geophysical strategy; thus the buried trench and geophysical strategies are not checked off on Table 4.1-1. Including extra access tubes in monitoring plans, even if not used extensively during site characterization and preoperational monitoring phases, could be very advantageous in the future.

## *4.2* Choosing different monitoring strategies

The wide variety of environmental and anthropogenic conditions that could be encountered at any single disposal site precludes the prescription of monitoring strategies without site specific information. In this section, we attempt to list the major factors that could influence the suitability of the four alternative strategies considered in this document. For each factor, we define opposing conditions (e.g., shallow water table to deep water table) and categorized each strategy as whether the condition supported its use, weakened its use, or made no difference with respect to its use (Table 4.2-1). Moreover, it must be noted that the use of these strategies, given specific site conditions, relies strongly on the goals and subgoals of the *monitoring program. For example, if the monitoring goals* stress early warning of releases at the base of a disposal unit, and the water table is shallow, then most geophysical devices will not be able to resolve the small changes in soil water content that could signal a release. Thus, the strategy likely would not be well chosen.

Our conclusions and recommendations are based on our experience with the strategies at the Maricopa site, and we recognize that our experiences may differ from the experiences of others. Nonetheless, we believe that the conditions and factors represent a good range of what might be expected in the field and how they affect the choice of monitoring strategies. This section provides a brief discussion of the factors and our conclusions on the use of different strategies.

### 4.2.1 Natural site conditions/processes

- Consolidation of subsurface material

Consolidated, unsaturated subsurface material would make trench excavation or large-diameter drilling very difficult. Installation of the monitoring trench at the Maricopa site likely would not have been feasible if the material was *consolidated, e.g., sandstone or fractured igneous rock.* Borehole installation through consolidated or unconsolidated material is well known, so the material at the site may have no bearing on the use of the BM strategy. The choice of using instruments that support the GM strategy also may be independent of the consolidation of the subsurface material because excavation is not needed. If the subsurface material is soil or other unconsolidated material, then excavation can be done more easily, favoring the MT and MI strategies.

- Soil texture

Clayey soils are normally conductive, which tends to reduce the precision of geophysical methods. Downhole GPR was attempted prior to Experiment 2, but the soils were found to be too conductive when borehole placement was 10 m apart. The sandier soils at the Maricopa site were more conducive for monitoring with geophysical methods, except in the presence of very coarse sand and gravel. *We found that the* low water holding capacity of these materials caused

Table 4.2-1. Specific site conditions and processes: how they affect the choice of monitoring strategies. MT, MI, BM, GM correspond to monitoring trench, monitoring island, borehole monitoring and geophysical monitoring, respectively.

| | Supports | Neutral | Weakens |
|---|---|---|---|
| **Natural site conditions/factors** | | | |
| Type of subsurface material: | | | |
| Consolidated | | BM, GM | MT, MI |
| Unconsolidated | MT, MI | BM, GM | |
| Soil texture: | | | |
| Clayey | | MT, MI, BM | GM |
| Sandy | GM | MT, MI, BM | |
| Precipitation: | | | |
| Heavy | | BM, GM | MT, MI |
| Light | MT, MI | BM, GM | |
| Depth to water table: | | | |
| Deep | MI, BM (unsat) | MT, GM | |
| Shallow | BM (sat) | MT, MI | GM |
| Wetness of soil material: | | | |
| Wet/Moist | MT, MI | BM | GM |
| Dry | BM | MT, MI, GM | |
| **Anthropogenic site conditions/factors** | | | |
| Proximity to population centers: | | | |
| Distant | MT, MI | | BM, GM |
| Close | BM, GM | MT, MI | |
| Existing buildings/plumbing: | | | |
| Present | BM | MI | MT, GM |
| Absent | | All | |
| Facility status: | | | |
| Operating | MT, MI, BM | GM | |
| Closed | GM | BM | MT, MI |

Table 4.2-1. Specific site conditions and processes: how they affect the choice of monitoring strategies. MT, MI, BM, GM correspond to monitoring trench, monitoring island, borehole monitoring and geophysical monitoring, respectively. (Continued)

| | Supports | Neutral | Weakens |
|---|---|---|---|
| **Anthropogenic site conditions/factors** | | | |
| Accessibility of heavy equipment: | | | |
| Accessible | All | | |
| Inaccessible | GM | | MT, MI, BM |
| Availability of AC power: | | | |
| Available | MT, MI | BM, GM | |
| Unavailable | BM, GM | | MT, MI |
| Cellular telephone coverage: | | | |
| In-range | MT, MI | BM, GM | |
| Out-of-range | BM, GM | MT, MI | |
| Lifespan of monitoring program: | | | |
| Long-term | GM, BM | | MT, MI |
| Short-term | All | | |

smaller changes in soil water content during the water input phase, reducing the ability of the devices to resolve changes in bulk electrical conductivity and resistivity. Devices that supported the other three strategies appeared to operate without effects from the texture.

- Precipitation

Precipitation rates are normally heavier at Eastern U.S. sites than at Western U.S. sites. None of the monitoring strategies is particularly well suited to locations experiencing heavy precipitation, but the MT and MI strategies in particular could be adversely affected. This is because of the potential problem with preferential flow of water through backfill material in the trench and island material, not because of the potentially shallow water table. Preferential flow of water could reduce the representativeness of the data, leading to false conclusions that soil water content has changed. This could be especially problematic in the case of the MT strategy, if constructed similar to that at the Maricopa site, where a neutron probe access tube was installed directly in the base of the trench. During the field infiltration experiments, we observed near surface fast flow paths that were attributed to bulk-soil properties, but not necessarily to backfill. Without the presence of numerous instruments in the trench, we would not have been able to make this conclusion. The MT and MI strategies could be supported at sites experiencing light precipitation where preferential flow may not be a significant problem, or where significant excavation and backfilling is occurring, but in such a way to be independent of precipitation. We do not believe that the precipitation rate affects the choice of either the BM or GM strategy to any significant degree.

- Depth to water table

We are not defining a specific depth as being deep or shallow, but we look at depth as being relative to the ability to install monitoring instruments and the goals of the monitoring program. For example, the presence of deep water tables may require one to monitor water content or constituent concentrations in the unsaturated zone. The presence of a deep water table supports the use of both MI and BM strategies because of the ability of these strategies to define vertical distributions of subsurface conditions in the unsaturated zone for gradient calculations. Because the MT and GM strategies are normally limited to monitoring near surface conditions (with the exception of the ERT method), measurement of vertical gradients may not be possible. If, for example, the subgoals of the monitoring program require the assessment of spatial variability along the trench, then the presence of a deep water table would support the use of the MT strategy. For sites with a shallow water table and an emphasis on groundwater quality, the BM strategy is most useful. The MT and MI strategies are both unaffected by a shallow water table, unless the base of the excavation intersects the capillary fringe during the year. In these cases, wiring from the monitoring instruments could become submerged and potentially damaged.

- Wetness of soil material

Of particular interest during Experiment 2 was the apparent lack of detection of the wetting fronts by the GM devices. In each case of poor detection, changes in bulk electrical conductivity and resistivity were too low for accurate tracking of the wetting front. Therefore, if the soil is initially moist, and the goal of the monitoring program is to detect changes in soil water content as a result of infiltration or leachate release, then relying on GM could become problematic. MT and MI strategies in wet soils allow a wider range of devices to be used, such as tensiometers and solution samplers. In dry soil, especially when they are too dry to use tensiometers and solution samplers, borehole monitoring may be advantageous relative to the other strategies.

### 4.2.2 Anthropogenic site conditions/processes

- Proximity to population centers

The relative proximity of the disposal site to population centers or transportation networks improves overall access to the site. For sites that are close to these hubs (e.g., several SDMP sites), frequent travel for data collection using BM and GM strategies may not result in substantially higher costs to the operator of the monitoring program. However, relying on BM and GM strategies for monitoring a distant site without easy access could increase program costs due to longer travel time for personnel. In these circumstances, choosing reliable, low-maintenance instruments (e.g., heat dissipation probes) could reduce the number of visits to the site and hence reduce the cost.

- Existing buildings/plumbing

Buildings and subsurface plumbing are more likely to be present at SDMP sites than at facilities specifically designed and constructed for housing waste material. Presence of these structures can be problematic for the MT strategy which relies on relatively long excavated cuts into the soil. If the contaminated material is stabilized on site, then it might be difficult to avoid some of these structures. Also, geophysical monitoring is usually negatively affected by the presence of metallic structures, thereby increasing background noise and causing potential loss of data points. This occurred at several locations at the Maricopa site because of the presence of subsurface AC power lines. The BM has a much smaller disturbed area (just the borehole diameter and a small support area around the borehole), so this may be the most useful monitoring strategy under these conditions. For newer LLW facilities, this factor should not significantly affect choice of monitoring strategy.

- Facility status

While the facility is operating, personnel are present at the site almost daily, enhancing security and maintenance of monitoring equipment. Data can be evaluated at the site and systems can be upgraded or repaired more easily. High maintenance systems, such as tensiometers and (in our case) TDR, required higher staff effort to ensure good data. Remote downloading and analysis of data from off-site locations may indicate when device output begins to drift; however, we found that daily observations of instrument status (e.g., manual measurements of tensiometer air space) greatly improved the reliability of the measurements. Once the facility is closed, and visits to the facility are less frequent, those higher maintenance instruments should be de-emphasized, especially if they are used in data acquisition systems. The geophysical monitoring strategy can be very useful for non-intrusive data collection after site closure because the instrument is taken to and removed from the site after each data collection episode. Data and instrument reliability can be evaluated quickly, if needed.

- Accessibility of heavy equipment

While the facility is open and earthmoving equipment is present onsite, installing trenches, monitoring islands, etc. is relatively easy. Monitoring programs can be expanded through installation of new trenches or islands, or reduced by decommissioning these features. Drilling equipment can also be brought to the facility with fewer chances of disrupting operations. After site closure, however, large disturbances to the site could affect the integrity of the disposal system. For this reason, use of MT, MI and BM strategies is weakened for sites that are closed, where future installation or trenches, islands or boreholes will be needed, or where decommissioning of these features is pending. Some cause for concern could be warranted if the facility closure plan calls for a small support or buffer area, and the monitoring islands or trenches are relied upon for the majority of the data collection. Because many of the GM devices are portable and nonintrusive, data collection can continue without the need for equipment or large support areas.

- Availability of AC power

The presence of AC power can be a significant advantage for those monitoring programs that rely on high current-drain instruments, such as TDR or vacuum pumps for solution samplers. These devices are commonly used to support the MT and MI strategies. We delivered AC power to several locations at the Maricopa site to supply power to vacuum pumps for solution samplers, to battery chargers, TDR cable testers, and data loggers. [We eventually removed the cable testers from AC power during water content sampling, then placed them back onto AC power during quiescent periods to recharge the batteries]. With the level of data collection and data transfer used during the field experiments, DC power alone with batteries recharged using solar panels, likely would not have been a sufficient power source. Installing high power-consuming monitoring devices to support strategies at disposal sites may be difficult without reliable AC power. Because many downhole (e.g., neutron probe) and EM instruments operate only on rechargeable batteries, the presence of AC power is convenient but not required.

- Telephone coverage

Telephone links (cellular or landline) to data loggers allow direct downloading of data and information to off-site personal computers. Thus, because of the emphasis of automated measurement systems to support the MT and MI strategies, presence of data lines could be very economical. Given that the BM and GM strategies traditionally require on-site personnel for data collection, automated data collection is not a significant issue, and hence neither is the need for telephone coverage. However, the case for using deep tensiometers or other electronic monitoring devices in boreholes could be greatly strengthened if data lines are present and instruments are connected to data loggers. If the field site is not accessible by telecommunications, then it may be more appropriate to focus on manual data collection, such as with BM and GM strategies.

- Lifespan of monitoring program

We believe that long-term monitoring programs (e.g., greater than 10 years) can benefit from the installation of access boreholes. As we stated above, future developments in downhole instrumentation could improve the accuracy in monitoring subsurface conditions, and the presence of access tubes could facilitate the testing and use of these instruments. The use of non-intrusive methods is also strengthened by the need for long-term monitoring if the goals of the monitoring program include the monitoring of near-surface soil water conditions. Long-term monitoring programs that rely heavily on the MT strategy could be affected by failure of monitoring devices, their associated wiring, and logging systems. During Experiments 1 and 2, we experienced a number of instrument failures that required either ongoing maintenance or replacement. In several instances (e.g., trench tensiometers), replacement would have required intrusive activity, which would have been a potentially difficult task if excavation through engineered barriers was needed. Though the MI strategy also requires a significant amount of wiring, they are easily replaced, thus prolonging the use of the monitoring systems. Therefore, if the monitoring goals require long-term monitoring of soil water conditions, then the program should include access tubes, or a combination of access tubes and the MI strategy. This will increase the flexibility of the overall monitoring program.

## 4.3 Analysis of Monitoring Systems

Regardless of the number of subgoals that are identified for a monitoring program and whether the monitoring strategies will work within that framework, it will likely require a combination of strategies in order to adequately survey changes in site conditions, especially if the facility is located in a geologically or structurally complex area. Moreover, the difficult task of identifying the number of devices, their locations and the sampling frequency for each instrument is complicated by the fact that each instrument needs to be matched to the site conditions expected for long-term post-closure periods.

This question of coverage cannot be answered without site specific information. However, we know that the monitoring program must provide data which shows that the disposal site is, or is not, performing acceptably. Therefore, the monitoring system is designed and operated so that potential releases are detected (i.e., undetected releases are minimized), whether to the saturated or unsaturated zone. However, objective analyses for evaluating monitoring systems are lacking in the literature, and this lack of methodologies introduces the potential for subjectivity in both the design and review of monitoring systems.

One way to remove this subjectivity would be to analyze the ability of the monitoring program to detect releases in a repeatable and objective manner. Several approaches to monitoring systems analysis have been proposed in the literature, using a variety of numerical approaches. In the work by Warrick et al. (1998b), we sought to develop a simplified procedure that could be added to existing and often-used numerical models that predict future subsurface conditions. The result of our analysis is a value which indicates the likelihood that a release from the disposal unit will be detected by the monitoring system, which we termed "monitoring efficiency." Larger values indicate that a larger percentage of releases will be detected, and smaller values mean that fewer releases will be detected. Thus, larger releases and more monitoring points would generally lead toward higher likelihood of detection. The analytical procedure optimizes the countervailing need to maintain a cost-effective monitoring program, while improving the site coverage.

Briefly, the detection method uses the following steps:

1. Develop a numerical model to predict possible release scenarios to the soil and/or groundwater. Determine

the center and standard deviation (SD) of the release.

2. Take the domain of interest, and divide it into pixels. Each pixel is assigned a probability p(x,z) that a spill will occur, and then normalized according to the size of the pixel; the sum of all p(x,z) values equals unity. The probability values come from the results of the numerical modeling.
3. Overlay the proposed monitoring scheme onto the domain of pixels, and assign coordinates to them. For example, a tensiometer would be assigned a single x, z coordinate; a neutron probe access tube can be represented by a series of x,z points.
4. Choose a spill with user-defined characteristics and place it in the center of a pixel.
5. Given the size and orientation of the spill, determine whether the spill intersects a device location. If the answer is yes, then $h_{i,j} = p(x,z)$, where i,j are the pixel coordinates; if the answer is no, then $h_{i,j} = 0$.
6. Repeat the steps for all pixels, and calculate the probability of detection as the sum of $h_{i,j}$ for all values of i,j.

The procedure was tested using a number of theoretical examples, as well as the monitoring points installed at 1.5 m depth at the Maricopa site. By rerunning the algorithm several times for different-sized releases, an X-Y scatterplot was developed that showed how release size affected the likelihood of detection. We did not implement the algorithm using specific water movement data from the experiments at Maricopa, because the constant flux boundary condition would have provided ambiguous results (i.e., all the monitoring strategies would have recorded 100% detection because the release encompassed the entire monitored region). However, the results using the theoretical examples clearly show the dependence on a number of factors which can be either implemented or measured in the field. The methodology can be used as a planning tool to optimize the locations and numbers of devices at the site, during current and future monitoring programs, if the goals and objectives of the program change with time.

# 5 SUMMARY

Three overall goals were identified for the development and implementation of monitoring programs. First, the monitoring program must be capable of detecting releases from the disposal site before they reach the facility boundary. Second, the monitoring program should emphasize strategies and systems that are as maintenance free as possible, especially during the long-term phase. Three, the monitoring program should stress the use of redundant monitoring systems, so that primary performance measures are obtained using more than one system.

Four strategies for monitoring the soil water conditions in the unsaturated zone were defined, tested in the field, and compared to each other with respect to their characteristics and ability to achieve the goals of the monitoring program during post-closure time periods. The four strategies included: 1) monitoring trenches - wide or narrow trenches, into which instruments can be installed along a transect; 2) monitoring islands - large diameter boreholes drilled vertically into the soil, allowing monitoring instruments to be installed into undisturbed material; 3) borehole monitoring - vertical and horizontal boreholes used for monitoring; and 4) geophysical monitoring - intrusive and non-intrusive methods for measuring bulk electrical properties of soil.

Quantitative comparisons of the strategies were not made, because of the wide variability of potential monitoring programs at actual disposal sites, and the limited applicability that our comparisons would have when applied to other sites. Rather we looked at the strengths and weaknesses of each strategy with respect to installation, maintenance and replacement. These could be essential considerations when choosing the strategy(ies) for another particular site, depending on the specific design criteria and ambient environmental conditions. Below is a summary of our comparisons:

1. Monitoring trenches - With a potentially long length, and open access to direct installation of instruments, trenches permit long distances to be monitored, though only at shallow depths. The soil material can be directly sampled and observed while the trench is open, but once closed (backfilled), access is lost. Monitoring instruments can be precisely placed along the transect. However, maintenance and replacement are difficult because of the need to potentially disrupt the subsurface soil material during these activities. The trenches strategy can be combined easily with other strategies that stress more intensive measurements over shorter distances.

2. Monitoring islands - This strategy permits excellent monitoring of vertical transects of soil water conditions, because the islands can be potentially installed to depths exceeding 10 m. Using the general design from the Maricopa site experiments, instruments can be installed at any depth and any radial orientation from the island. Soil samples can be collected at any time because the island is not permanently sealed. However, the island strategy, when used alone, is limited with respect to spatial resolution unless multiple islands are used. Instrument maintenance and replacement are easier than other strategies, given their proximity to the island walls and the general accessibility of the islands themselves.

3. Borehole monitoring - This traditional monitoring strategy has distinct advantages over other strategies because no practical depth limitation exists for installation; monitoring wells and access tubes can be drilled to almost any depth. A wide variety of completion designs can be implemented, including the use of fixed-point instruments. Soil samples can be collected continuously during drilling, but, generally, not after the borehole is completed. Some limitations exist in terms of the number of devices that can be placed in each borehole, reducing the flexibility during program design. Maintenance and replacement of permanently-installed devices is not practical, requiring abandonment and redrilling. Expanding the number of monitoring points requires additional drilling, but this can often be done with minimal site disturbance.

4. Geophysical monitoring - Though measurement of bulk electrical properties cannot easily be converted to primary performance measures, the combination of

intrusive and non-intrusive techniques provides flexibility in long-term program design. The EM-31 and -38 instruments are portable, easy to use and require no installation other than site surveying. Research has shown that the method can be used for profiling water contents in shallow soils, though we were unable to confirm this in the initially wetted soils during Experiment 2. The borehole tomography method appeared to effectively measure wetting front migration during Experiment 1; however, it was difficult to ascertain the lower limit of water content change for soils with low water holding capacity and whether the method would be limited by this. The ERT method is potentially limited by an inability to maintain or replace the sources/conductors in the borehole during long time periods. New monitoring points can be installed, but this could affect the rather specific geometric arrangements required for the boreholes.

Section 4 (Discussion), divided into monitoring program subgoals and site conditions and processes, summarizes the general implications of these factors on the choices of monitoring strategies. We identified 12 subgoals, all of which are compatible with the three major goals described in Section 2. They are intended to help define the important aspects of the monitoring program. Each subgoal is briefly explained, and we then describe whether the monitoring strategy would be useful in satisfying or addressing the subgoal. Many times, only one or two strategies would be useful and in some cases, all four strategies would be useful. For example, if a goal of the monitoring program is to quantify and monitor hydraulic gradients in deep soils, then the monitoring island and borehole monitoring strategies would help to satisfy those goals. Monitoring trenches are very shallow, and are not well suited for multiple instruments installed in vertical transects; geophysical monitoring instruments (as used in this study) are not designed for measuring hydraulic gradients, because 1) they have poor resolution in the vertical dimension, and 2) electrical conductivity is affected by water content and not water tension. Other examples similar to this are discussed. The second subsection in Section 4 deals with site conditions and processes and how they affect the choices of possible monitoring strategies. We further subdivided these into natural (e.g., precipitation, depth to water table) and anthropogenic (e.g., presence of buildings) conditions. A total of 12 site conditions were identified and opposing conditions were defined (e.g., shallow/deep water table). We then categorized each strategy as to whether the condition supported its use, weakened its use, or made no difference with respect to its use within an overall monitoring program. When used in combination with the subgoals, the choice which strategy (or combination of strategies) to use becomes more clear.

The controlled flux experiments conducted at the Maricopa site provided a large set of data and information that can be used for directly comparing numerous monitoring systems, which were chosen to support four monitoring strategies, and for studying other aspects of monitoring systems that are not directly related to the field experiments. Three such studies were undertaken, ranging from analysis of monitoring programs to correction of individual monitoring instruments. Other future studies will be initiated using the existing database.

# 6 REFERENCES

Borchers B, T. Uram, and J.M.H. Hendrickx, Tikhonov regularization of electrical conductivity depth profiles in field soils, Soil Sci. Soc. Am. J., 61,1004-1009, 1997.

Dictionary of Science and Technology, Academic Press., San Diego, CA, 1992.

Driscoll, F.G., Groundwater and wells, Johnson Division, St. Paul, MN, 1986.

Eppstein, M.J. and D.E. Dougherty, Efficient three-dimensional data inversion: soil characterization and moisture monitoring from cross-well ground-penetrating radar at a Vermont test site, Water Resour. Res., 34, 1889-1900, 1997.

Franke, O.L. and the Ground-water Focus Group, Conceptual frameworks for ground-water quality monitoring, Ground-water Focus Group, Intergovernmental Task Force on Monitoring Water Quality. Denver, CO, 1997.

Gee., G.W., A.L. Ward, R.R. Kirkham, Effect of available water capacity on the performance of capillary barriers, Am. Geo. Union. Fall Meeting, San Francisco, CA, 1998.

Gilbert, R.O., Statistical methods for environmental pollution monitoring, van Norstrand Reinhold, New York, 320 pp., 1987.

Hubbard, R.K., L.E. Asmussen, H.F. Perkins, Use of ground-penetrating radar on upland Coastal Plain soils, J. of Soil and Water Conservation, 45, 399-405, 1990.

Kachanoski, R.G., E.G. Gregorich, and I.J. van Wesenbeeck, Estimating spatial variations of soil water content using noncontacting electromagnetic induction methods, Can. J. Soil Sci., 68, 715-722, 1988.

Kung, K.J.S., and Z.B. Lu, Using ground penetrating radar to detect layers of discontinuous dielectric constant, Soil Sci. Soc. Am. J., 57, 335-340, 1993.

Ledieu, J., P. de Ridder, P. de Clark, and S. Dautrebande, A method of measuring soil moisture by time-domain reflectometry, J. Hydrol., 51, 113-1121, 1986.

McNeill, J.D, Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters, *In* Advances in measurement of soil physical properties: Bringing theory into practice, SSSA Special Publication No. 30, Madison, WI, 1992.

Meyer, P.D., M.L. Rockhold and G.W. Gee, Uncertainty analyses of infiltration and subsurface flow and transport for SDMP site, NUREG/CR-6565, U.S. Nuclear Regulatory Commission, Washington, DC, 1997.

Post, D.F., C. Mack, P.D. Camp, and A.S. Suliman, Mapping and characterization of the soils on The University of Arizona Maricopa Agricultural Center, Proc. of the American Water Resources Association, Hydrology and Water Resources in Arizona and the Southwest, 18, 49-60, 1988.

Scanlon, B.R., J.G. Paine, R.S. Goldsmith, Evaluation of electromagnetic induction as a reconnaissance technique to characterize unsaturated flow in an arid setting, Groundwater, 37, 296-304, 1999.

Scanlon, B.R., W.F. Mullican III, R.C. Reedy, and E S. Angle, Prototype engineered barrier designs for low-level radioactive waste disposal in Texas, *In* Landfill Capping in the Semi-Arid West: Problems, Perspectives, and Solutions. Conference Proceedings, Env. Sci. and Res. Fndn. ESRF-019, 1997.

Soil Conservation Service, Soil Survey: Eastern Maricopa and Northern Pinal Counties Area, Arizona, USDA/SCS, U.S. Government Printing Office, Washington, DC, 1974.

U.S. NRC, 1998 Web site: http://www.nrc.gov/NRC/CFR/PART061/part061-0002.html, 1998a.

U.S. NRC, 1998 Web site: http://www.nrc.gov/NRC/CFR/PART061/part061-0053.html, 1998b.

U.S. NRC, 1998 Web Site: http://www.nrc.gov/NRC/CFR/PART060/part060-0002.html, 1998c.

Vachaud, G., A. Passerat DeSilands, P. Balabanis, and M. Vauclin, Temporal stability of spatially measured soil water probability density function, Soil Sci. Soc. Am. J., 49, 822-828, 1985.

van Overmeeren, R.A., S.V. Sariowan, and J.C. Gehrels, Ground penetrating radar for determining volumetric soil water content; results of comparative measurements at two test sites, J. Hydrology, 197, 316-338, 1997.

Warrick, A.W., P.J. Wierenga, M.H. Young, and S.A. Musil, Diurnal fluctuations of tensiometric readings due to surface temperature changes, Water Resour. Res., 34, 2863-2869, 1998a.

Warrick, A.W., M.H. Young, and P.J. Wierenga, Probabilistic analysis of monitoring systems for detecting subsurface contaminant plumes, Ground Water, 5, 894-900, 1998b.

Young, M.H., P.J. Wierenga, A.W. Warrick, L.L. Hofmann, S.A. Musil, B.R. Scanlon, and T.J. Nicholson, Field testing plan for unsaturated zone monitoring and field studies, NUREG/CR-6462, U.S. Nuclear Regulatory Commission, Washington, DC, 1996.

Young, M.H., P.J. Wierenga, A.W. Warrick, L.L. Hofmann, and S.A. Musil, Monitoring soil water during a field-scale infiltration experiment, Agron. Abstracts., Am. Soc. Agron., Madison. WI, 1997.

Young, M.H., P.J. Wierenga, A.W. Warrick, L.L. Hofmann, and S.A. Musil, Results of field studies at the Maricopa Environmental Monitoring Site, Arizona, NUREG/CR-5694, U.S. Nuclear Regulatory Commission, Washington, DC, 1999.

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

## BIBLIOGRAPHIC DATA SHEET

*(See instructions on the reverse)*

1. REPORT NUMBER
**(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)**
NUREG/CR-5698

2. TITLE AND SUBTITLE
Comparing Monitoring Strategies at the Maricopa Environmental Monitoring Site, Arizona

3. DATE REPORT PUBLISHED
MONTH: July
YEAR: 1999

4. FIN OR GRANT NUMBER
JCN W6151

5. AUTHOR(S)
M.H. Young, A.W. Warrick, P.J. Wierenga, L.L. Hofmann and S.A. Musil

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(Inclusive Dates)*
04/95 - 02/99

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Department of Soil, Water and Environmental Science
University of Arizona
Tucson, AZ 85721

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
T.J. Nicholson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

The purpose of this document is to discuss the alternative monitoring strategies used during field experiments at the Maricopa Environmental Monitoring site, Maricopa, AZ. The strategies selected could potentially be incorporated into monitoring programs at low-level radioactive waste disposal facilities. The four monitoring strategies include: Monitoring Trenches, Monitoring Islands, Borehole Monitoring, and Geophysical Monitoring. Strengths and weaknesses of each strategy were described with respect to installation, maintenance and replacement of monitoring systems and instruments. Evaluation of the strategies was mostly qualitative in nature, but were supported by data collected during two, field-scale infiltration experiments in the vadose zone. Each of the strategies possess benefits and drawbacks, requiring site specific analyses of site and environmental conditions during monitoring program design. The document also presents the concept of primary performance measures (e.g., water content, water tension and solute concentration), each of which directly influences water movement and contaminant migration from disposal sites, and discusses the need to accurately convert field observations to these primary measures. Using multiple instruments whose data convert to the same primary performance measure, could improve the confidence that changes in soil water conditions are real and not affected by the monitoring systems themselves.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Hydrology
Borehole Monitoring
Geophysical Monitoring
Monitoring Islands
Monitoring Programs
Monitoring Strategies
Monitoring Trenches
Performance Measures
Subsurface Monitoring
Unsaturated Zone

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
*(This Page)* unclassified
*(This Report)* unclassified

15. NUMBER OF PAGES

16. PRICE

Printed
on recycled
paper

Federal Recycling Program

**UNITED STATES**
**NUCLEAR REGULATORY COMMISSION**
WASHINGTON, DC 20555-0001