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# YUCCA MOUNTAIN PROJECT
# STUDY PLAN APPROVAL FORM

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Study Plan Number 8.3.1.2.2.1 R0

Study Plan Title Characterization of Unsaturated-Zone Infiltration

Revision Number R0

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# 1 PURPOSE AND OBJECTIVES OF STUDY

## 1.1 Purpose of the Study Plan

The U.S. Geological Survey (USGS) is conducting studies at Yucca Mountain, Nevada, as part of the Yucca Mountain Project (YMP). The purposes of the USGS studies are to provide hydrologic and geologic information to evaluate the suitability of Yucca Mountain for development as a high-level nuclear-waste repository and the ability of the mined geologic-disposal system (MGDS) to isolate the waste in compliance with regulatory requirements. This study is designed to collect and evaluate data required to assess the performance of the Yucca Mountain Site with respect to the requirements of Federal Regulations 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191.

This study plan describes the USGS plans for surficial hydrologic and shallow-unsaturated zone characterization of Yucca Mountain. The study is organized into three activities:

- o 8.3.1.2.2.1.1 - Characterization of hydrologic properties of surficial materials;
- o 8.3.1.2.2.1.2 - Evaluation of natural infiltration; and
- o 8.3.1.2.2.1.3 - Evaluation of artificial infiltration.

Note that the numbers (e.g., 8.3.1.2.2.1.1) used throughout this plan serve as references to specific sections of the YMP Site Characterization Plan (SCP). The SCP (U.S. DOE, 1988) describes the technical rationale of the overall site-characterization program and provides general descriptions of the activities described in detail in Section 3 of this study plan.

Figure 1.1-1 illustrates the location of the study within the SCP geohydrology program. The unsaturated-zone infiltration study is one of nine studies planned to characterize the unsaturated zone at Yucca Mountain. Seven of the studies are surface-based evaluations and two studies, (8.3.1.2.2.4 - Percolation study in the exploratory-shaft facility and 8.3.1.2.2.5 - Diffusion tests in the exploratory-shaft facility), will study the *in situ* hydrologic characteristics of Yucca Mountain from shafts and underground drifts. The three activities in this study were selected on the basis of a number of factors, including design/performance-parameter needs, available test/analysis methods, test scale, time requirements, and schedule constraints. (*Parameter* is used in this plan to mean a property, characteristic, and/or the numerical value of a constant that is used to describe the unsaturated-zone hydrologic system). These factors are described in Sections 2 and 3.

The plans for each activity are presented in Section 3. The descriptions include (a) objectives and parameters, (b) technical rationale, and (c) tests and analyses. Alternate test and analysis methods are summarized, and cross references are provided for technical procedures.

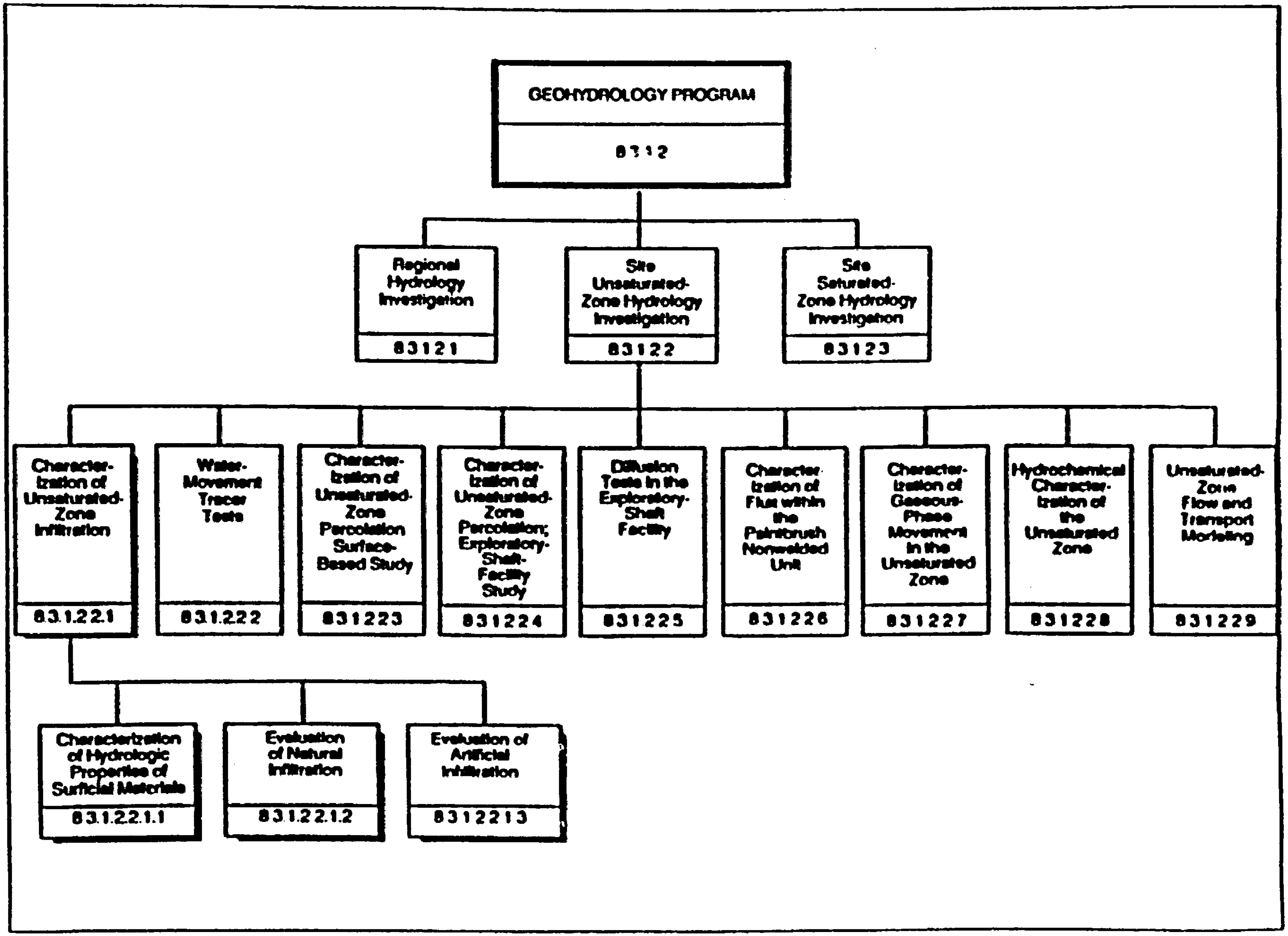



Figure 1.1-1. Diagram showing location of study within the unsaturated-zone investigation and organization of geohydrologic-characterization program.

Application of the study results is summarized in Sections 1.3 and 4; study and activity schedules and milestones are presented in Section 5, and a study-plan reference list is presented in Section 6. Quality-assurance procedures are documented in Section 7.1. Plans for surficial hydrologic-properties characterization, natural infiltration, and artificial infiltration are described in Sections 3.1, 3.2, and 3.3, respectively.

### 1.1.1 Prototype testing

The USGS investigators responsible for the activities described in Section 3 have chosen and proposed testing procedures that they expect will work as planned. The investigators recognize, however, that there is a degree of risk associated with many of the tests that have not been previously tried and have therefore planned prototype tests to evaluate the feasibility of the proposed testing methods. It can be expected that prototype testing and initial full-scale study may result in the need to change, adjust, abandon or further test the methods, but due to the multiple test approach, it is anticipated that the time allotted will be sufficient.

Prototype testing will serve several purposes, including the development of reasonable and adequate quality-assurance procedures and an assessment of the data acquisition and storage needs of individual tests. Primarily, prototype testing will provide an opportunity to understand, implement, and refine testing procedures prior to the actual field implementation of the methods. For example, the artificial-infiltration tests have never been performed at the proposed scales. Similarly, many of the proposed testing methods have never been applied to unsaturated, poorly-sorted alluvium or, fractured, surficial, bedrock exposures, such as those at Yucca Mountain. If these tests do not perform as the investigators expect them to conceptually, either due to design flaws or unanticipated *in situ* conditions, potentially critical licensing data could be lost. The only credible means to reduce this risk is to validate the test concepts and test designs, identify alternate procedures, and perform laboratory and field trials prior to site-characterization activities.

The prototype-test plans applicable to activities in this study plan (Section 3) are described in detail in project prototype-testing documents. These documents provide in-depth analyses and recommendations for 23 prototype tests (including those applicable to infiltration activities). The prototype-test plans include the purpose and objectives of the tests, the testing rationale and description, and a summary of the necessary instrumentation, equipment calibration, and materials for prototype testing.

Equipment selection and development is a major objective of the prototype testing. As such, specification of equipment to be used during site characterization cannot be completely defined until this testing is complete. For standard testing methods, equipment lists may be found in the technical procedures noted for each activity described in Section 3 of this plan.

The prototype-testing must be successfully completed before the site-characterization testing can begin. Characterization of the site may not be conducted by all of the methods described in this study plan if prototype testing indicates that some of these methods cannot be applied successfully to Yucca Mountain. It is not in the scope of this study plan to discuss the details of prototype testing. References are made to specific prototype tests in each of the activity descriptions of Section 3.

## 1.2 Objectives of the study

Hydrologic evaluation of the unsaturated zone will be conducted as an integrated set of surface- and subsurface-based activities with a common objective to provide an understanding of the past, present, and future flow characteristics of the unsaturated zone. The specific objective of the unsaturated-zone infiltration study is to define the upper flux boundary conditions (the upper 10 m, estimated to be the maximum rooting depth for any plant species on Yucca Mountain) for Yucca Mountain under both present-day and simulated future, wetter climatic conditions, which includes the evaluation of the spatial distribution of infiltration rate over the repository block. These boundary conditions are necessary to model flow through the thick unsaturated zone beneath Yucca Mountain. The flux-boundary conditions will be determined from infiltration experiments and other hydrologic data collected in the activities described in this report. Water flux at the land surface/atmosphere interface, whether as evaporation or infiltration, will directly affect recharge and flow rates through the repository block.

The objectives of the individual activities are.

- 8.3.1.2.2.1.1 - to characterize infiltration-related hydrologic properties and conditions of surficial materials;
- 8.3.1.2.2.1.2 - to characterize present-day infiltration processes and net-infiltration rates in surficial materials;
- 8.3.1.2.2.1.3 - to characterize the range and spatial variability of infiltration rates, flow velocities, and flow pathways in surficial materials; and to characterize the relation among precipitation, runoff, infiltration, perched water, and evaporation under varying climatic conditions.

Figure 1.2-1 shows the general vicinity of Yucca Mountain, the area in which the infiltration-related tests will be conducted. Additional maps showing detailed locations of boreholes and study plots for individual activities are in Section 3

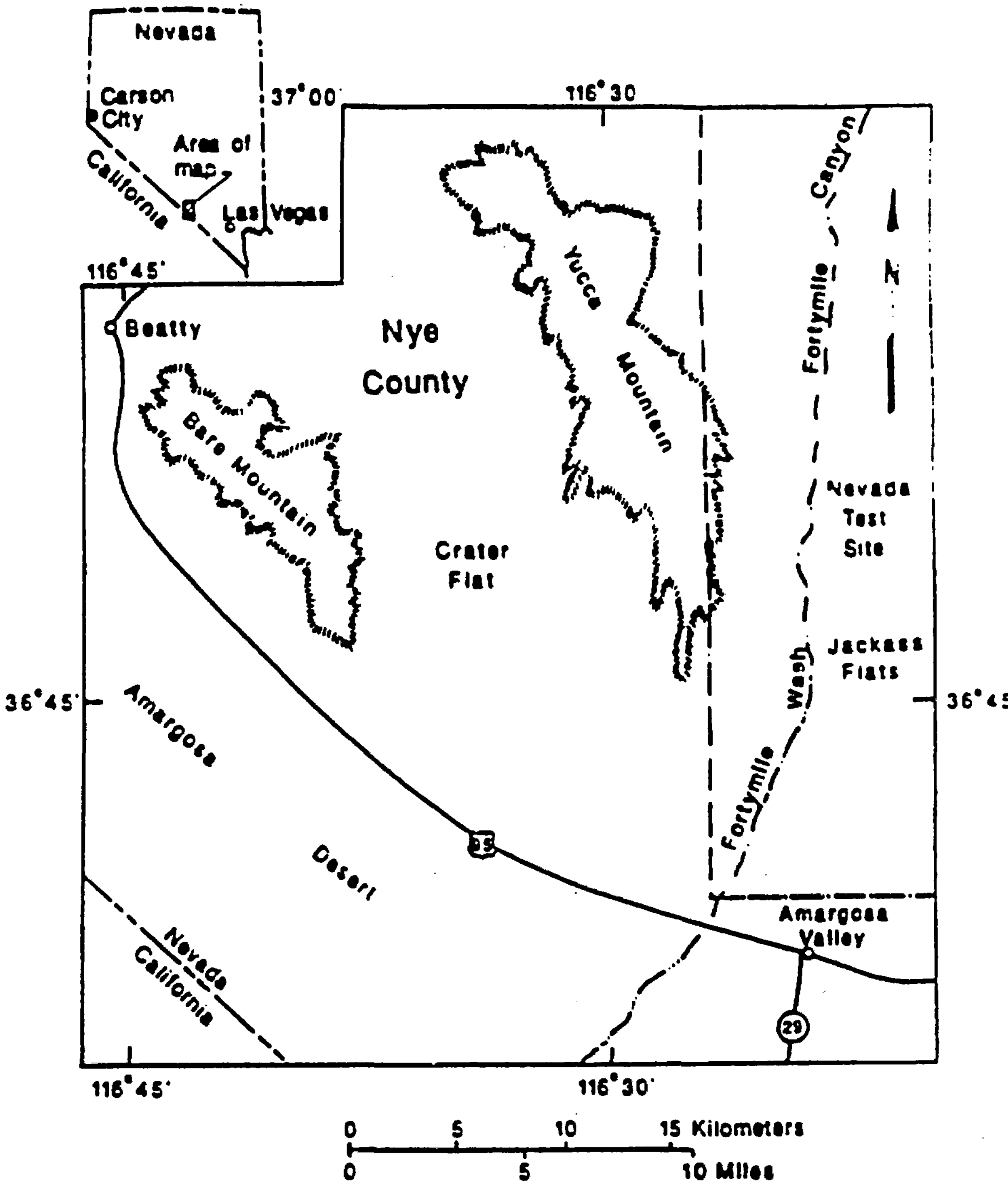



Figure 1.2-1. Map showing location of Yucca Mountain.

1.3 Regulatory rationale and justification

The results of unsaturated-zone infiltration characterization will provide hydrologic data needed for performance-assessment calculations of unsaturated-zone ground-water travel times and rates of radionuclide releases to the accessible environment. Hydrologic properties determined in the study will also be used in design analyses of the underground facility, repository seals, and waste packages.

The overall regulatory-technical relations between SCP design and performance information needs and data collected in this study are presented in the geohydrology testing strategy presented in SCP Section 8.3.1.2 and the issue-resolution strategies (repository, seals, waste package, and performance assessment) presented in SCP Sections 8.3.2 - 8.3.5. The description presented below provides a more specific identification of these relations as they apply to this study. A detailed tabulation of parameter relations is in Appendix 7.2.

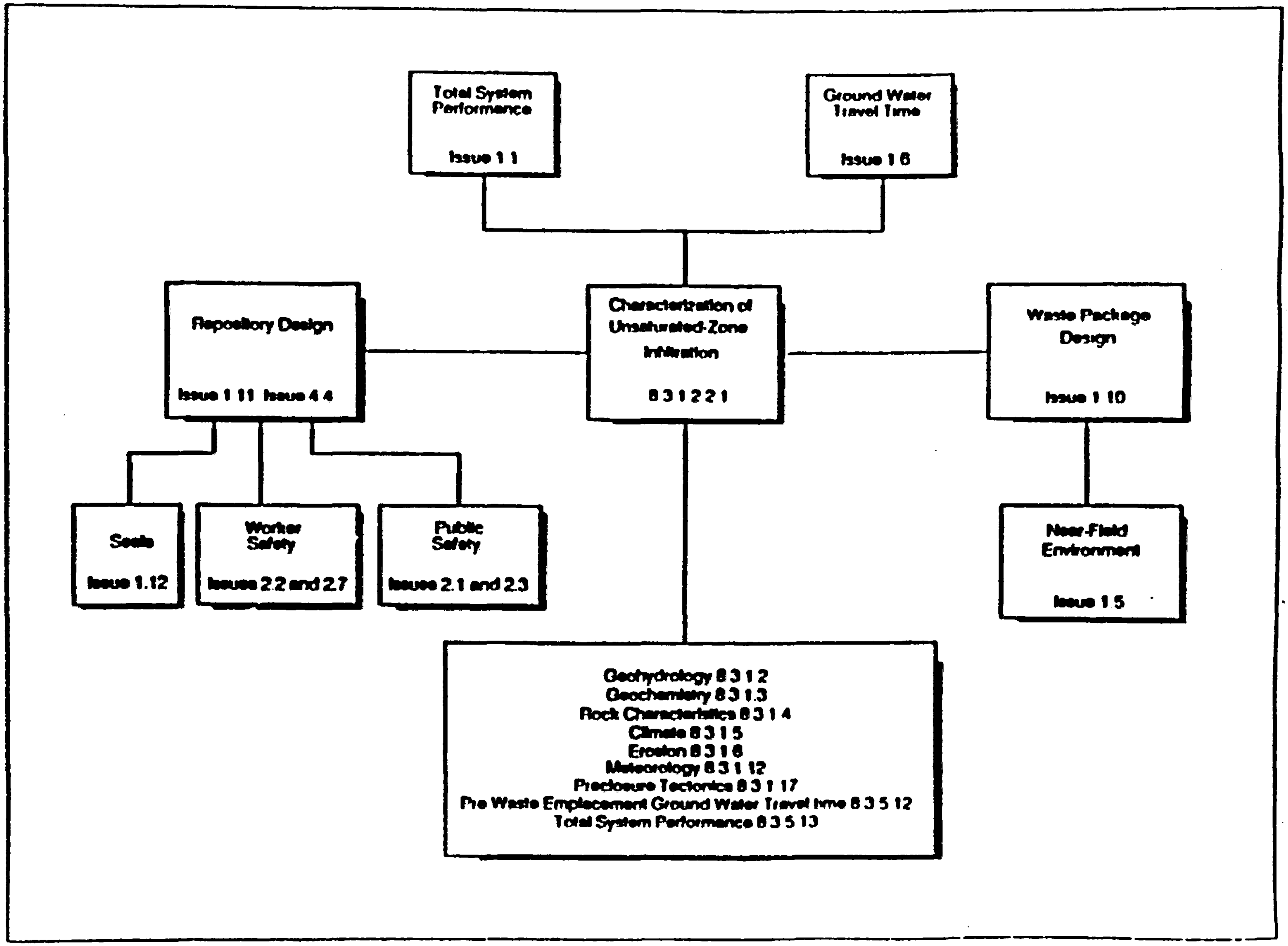
Project-organization interfaces between the unsaturated-zone infiltration study (8 3 1.2.2 1) and the YMP performance and design issues are illustrated in Figure 1.3-1. The figure also indicates project interfaces with other site studies; these relations are described further in Section 4.2. The relations between the design and performance issues noted below and the regulatory requirements of 10 CFR 60 and 10 CFR 960 are described in Section 8.2.1 of the SCP.

Information derived from the study will principally support the performance determinations of pre-waste-emplacement, ground-water travel time (Issue 1.6) and the predictions of radionuclide releases to the accessible environment (Issue 1.1). Study results will also provide information for the resolution of issues concerned with waste package design (Issue 1.10), releases from the repository engineered-barrier system (Issue 1.5), and repository design (Issues 1.11 and 4.4).

Physical and hydrologic information about the near-surface unsaturated zone obtained from this study will be used in the analyses for repository underground-facility design (Issue 4.4) and in the assessments of repository postclosure performance (Issue 1.11). Unsaturated-zone information on fracture characteristics and hydrologic conditions will be used in developing the design requirements for shaft and borehole seals (Issue 1.12). Information on the water conditions will be used in the analyses of waste-package performance (Issue 1.10).

Performance Issue 1.1
(Total-system radionuclide release to the accessible environment)

This issue requires that the geologic setting, engineered-barrier system, shafts, boreholes, and seals be selected and designed so as to limit the cumulative release of radionuclides for 10,000 years following permanent closure of this repository. Site information resulting from this study will be used to satisfy the requirements of numerous supporting parameters needed to evaluate the nominal case of Scenario Class E of the issue-resolution strategy for total system performance. The study results will also provide baseline data for the disturbed




F[illegible]re 1.3-1 Diagram showing interfaces of the un[illegible]urated-zone infiltration study with YMP perform[illegible]e [illegible] design issues and other site characterization p[illegible]ams

cases. Descriptions of the scenarios are given in SCP Section 8.3.5.13. These supporting parameters (e.g., hydrologic characteristics of the rock matrix, fracture network, or fault zones specific to the repository area) are used in calculations of the performance parameters for the different scenarios. Examples of performance parameters for the nominal case are average flux and average effective porosity in the unsaturated zone in the repository area.

The performance parameters for each of the scenario classes apply to expected partial performance measures (EPPM's). For example, Scenario Class E has three EPPM's: one for the unsaturated-zone liquid pathway, one for the saturated-zone liquid pathway, and one for the gas pathway. Determination of each of these EPPM's depends upon data from performance parameters, which in turn depend upon calculations from supporting parameters, which in turn depend upon site information collected in the this study. These relations are described in the SCP and are further documented in the tabulations of Appendix 7.2.

Knowledge of hydrologic properties is required for postclosure-performance evaluation of the near-field environment of the repository and underground openings. Data on Topopah Spring unit hydrologic properties resulting from this study, along with estimates of how these properties (or parameter values) may change due to climate changes, will be useful in computer modeling of engineered-barrier, system-release scenarios.

Performance Issue 1.6
(Pre-waste emplacement, ground-water travel time)

As in Issue 1.1, site information from the study will be used to satisfy numerous supporting performance parameters needed to assess ground-water travel time in individual unsaturated-zone units. These supporting parameters are used to define various aspects of the unsaturated-zone model, spatial correlation structure model, and fracture-hydrologic-characteristics model. These aspects include initial and boundary conditions, material properties, system geometry, and validation of model concepts. The results of the ground-water travel-time calculations yield performance parameters for each of the unsaturated-zone units. Examples of these performance parameters are fracture characteristics, flux, percolation rate, and volumetric-water content; these are applied to the performance measure of ground-water travel time for each hydrogeologic component of the ground-water regime.

Rock hydrologic and physical properties measured in this study are required for the calculation of ground-water travel time. For example, information on natural- and artificial-infiltration rates, surficial-material water content, and near-surface water-potential profiles will support the determination of upper flux boundary conditions for the ground-water travel-time model. Material properties such as porosity and hydraulic conductivity will be determined for a number of hydrogeologic units where they are exposed at the surface using both laboratory and *in situ* tests. This information is important to the determination of ground-water travel time for each of those units. Information on fracture characteristics from this study will also support these travel-time calculations.

Performance Issues 1.8 and 1.9
(Favorable and potentially adverse conditions) (Qualifying and disqualifying conditions)

The results of this study have indirect applications to the NRC siting criteria - Favorable Condition 7 (pre-waste-emplacement, ground-water travel time) through Issue 1.6, and Favorable Condition 8 (unsaturated-zone hydrogeologic conditions) through Issue 1.1. The study also has indirect applications to the higher-level findings for the geohydrology qualifying and disqualifying conditions through Issues 1.1 and 1.6.

Design Issue 1.10
(Characteristics and configuration of the waste package)

Unsaturated-zone transmissive properties (such as saturated and unsaturated hydraulic conductivity) and water-content information obtained from this study may be useful in characterizing the near-field (pre-waste-emplacement) environment of the waste packages by indicating zones near the surface where high water flow rate may be expected (i.e., fracture zones).

Information on the quantity of unsaturated-zone water obtained from this study will be used in assessing the performance of the engineered-barrier system in limiting the release of radionuclides. Hydrologic properties data of the Topopah Spring unit obtained from this study will be used in calculating the flow and transport in the near-field host rock. The performance parameters receiving site information are host-rock hydrologic properties.

The results of the this study will also support (indirectly through Issue 1.10) resolution of the performance issue concerned with releases from the engineered-barrier system (Issue 1.5) where the applicable performance measure is the concentration of radionuclide species in the gas phase, liquid water, and adsorbed to solid phases within the near-field host rock. Host-rock hydrologic properties collected in this study will apply to the hydrologic performance parameters of the issue.

Design Issue 1.11
(Characteristics and configurations of repository and engineered barriers - postclosure)

Postclosure characteristics and configurations of the repository underground openings will rely, in part, on the rock physical and hydrologic properties information derived from this study. Data on fracture characteristics will help support the determination of the potential for significant displacement. Possible changes in saturation and water chemistry in the near-field host rock will be supported by water-content information gathered in this study, in particular, fracture flow and geochemical analysis of infiltration water, as determined at the surface.

Preclosure assessment of repository characteristics and configurations (Issue 2.7, which is supported indirectly through Issue 1.11) will use

rainfall-runoff-infiltration relations determined by this study to support a variety of performance measures (such as surface flooding at the facility and volume of surface water flowing to nearby water bodies) which may affect worker safety.

Design Issue 1.12
(Characteristics and configurations of shaft and borehole seals)

Site information of surficial-hydrologic properties will be applied to the design and placement of the following sealing system elements: anchor-to-bedrock plug/seals, station plugs, and general fill. The saturated hydraulic conductivity, thickness, and water-content profiles of the alluvium, along with rainfall-runoff-infiltration relations, will be used in calculating the amount of surface waters entering the shaft that could potentially reach the waste disposal rooms of the underground facilities. Similarly, saturated bulk-rock hydraulic conductivities and erosion potential in the emplacement area are design and performance parameters supported by information from this study.

Design Issue 4.4
(Repository design and technical feasibility)

Data generated by the shallow unsaturated-zone infiltration studies address this issue in limited capacity. Surface hydrology data for different climatic scenarios, however, will be useful in the evaluation of facility designs that are not jeopardized by natural (e.g., surface runoff, floods) and man-made phenomena. Similarly, an understanding of infiltration/runoff ratios and hydraulically-induced erosion characteristics will lead to the development of facilities adequate to withstanding natural phenomena (i.e., meteorological) without damage to functional capability. Rainfall-runoff-infiltration relations characterized by this study will also support worker and public safety concerns (Issues 2.1, 2.2, 2.3, and 2.7).

The following paragraphs briefly summarize the information to be obtained by the activities of this study. More detailed descriptions are presented in Section 3.

The activity designed to characterize hydrologic parameters of surficial units (8.3.1.2.2.1.1) will provide an analysis of infiltration and related hydrologic data to define hydrogeologic-surficial units, each characterized by a different set of representative infiltration properties. The useful parameters this activity will evaluate are infiltration and runoff rates, porosity, density, water content, water potential, soil texture, and depth to bedrock.

The evaluation of natural infiltration (8.3.1.2.2.1.2) will provide information necessary for defining the upper-flux boundary conditions for each hydrogeologic-surficial unit. The parameters to be measured in this activity are infiltration rates, net infiltration, flow velocities, precipitation, runoff, and evapotranspiration.

The evaluation of artificial infiltration (8.3.1.2.2.1.3) will provide data on infiltration processes under different possible climatic conditions for each hydrogeologic-surficial unit. The parameters of this activity are

saturated- and unsaturated-infiltration rates, flow velocities, flow pathways, precipitation, runoff, evapotranspiration, saturated- and unsaturated-hydraulic conductivity and water content-water potential characteristic curves

Specific relations among the site parameters obtained from this study and their relations to the design and performance parameters are documented in Table 7.2-1 in the appendix of this plan.

# 2 RATIONALE FOR STUDY

## 2.1 Technical rationale and justification

This section provides an overview and justification of the overall study. Section 3 of this plan provides additional detail for the specific activities, tests and analyses, and methods to be used.

### 2.1.1 Statement of problem and test justification

Understanding the geohydrologic environment encompassing the unsaturated zone at Yucca Mountain is essential to site characterization because it is within this interval of rocks that the repository is proposed to be constructed. The geologic evaluation of the site is a multi-discipline task. Investigations are planned to study the geochemical and geologic characteristics (8.3.1.3, Geochemistry, and 8.3.1.4.2, Stratigraphy and Structure) and the thermal and mechanical properties of the rocks (8.3.1.15.1). It is not within the scope of this study plan, however, to discuss the rock-characteristic and geologic studies in detail. The reader is referred to the Site Characterization Plan (SCP) for descriptions of these studies. Only the unsaturated-zone infiltration tests, and the characterization of the surficial materials (soil and exposed bedrock) are discussed here.

It is important to evaluate water flow and storage within the repository block because water is an expected major medium for transport of radionuclides to the accessible environment. In addition, a thorough evaluation of water flow in the shallow unsaturated-zone surficial materials at Yucca Mountain is necessary, as it directly affects recharge and flow rates through the repository block as well as vapor flow and transport. In the unsaturated zone, water is present in both liquid and vapor phases within the interstitial, fracture, and lithophysal openings. Water flow and storage are envisioned to be complex, three-dimensional, spatially and time dependent; controlled by the structural, stratigraphic, and climatological settings at the site. Water flow is expected to occur in the liquid phase within interconnected pores and fractures, as well as by advective and diffusive vapor-phase flow within interconnected air-filled fractures and openings. The hydrologic evaluation of the site constitutes a problem of transient, two-phase, three-dimensional, coupled heat and water flow within a layered sequence of tilted, faulted, and fractured, variably saturated tuffaceous-geohydrologic units.

Characterization of the unsaturated zone beneath Yucca Mountain requires the use of many different tests performed under varying conditions and orientations, and at different locations and scales. It is important to understand ground-water flow and storage within the shallow unsaturated zone in order to understand the flow of water and vapor within the repository block. The surface boundary at Yucca Mountain is one of the most important boundaries to be characterized because through this boundary water and air can enter the unsaturated zone directly, and gases and water vapor can escape.

Prior to the beginning of the USGS's unsaturated-zone studies at Yucca Mountain, few, if any, flux data existed for any portion of the surface or subsurface. No attempts had been made to measure unsaturated-zone flux directly, although several indirect methods had been used to estimate flux into the repository block. The error in flux estimates can, however, be very large when indirect methods are used, as these methods are less precise and accurate.

The first method used to estimate flux assumed that recharge rates to the saturated zone were equal to deep unsaturated-zone fluxes (Montazer and Wilson, 1984). Both mass-balance methods for estimating recharge (Winograd and Thordarson, 1975) and empirical methods relating recharge to precipitation (Czarnecki, 1985), are subject to large errors. A flux of 0.5 mm (0.02 in) per year was estimated for Yucca Mountain using the mass-balance methods, and a rate of 0.7 mm (0.03 in) per year was estimated using an empirical relation and comparing the resulting mass balance with an analog ground-water basin. Using temperature data from various boreholes, Sass and Lachenbruch (1982) estimated a vertical-water flux of 1.0 to 10 mm (0.04 to 0.4 in.) per year in the combined saturated and unsaturated zones beneath Yucca Mountain. It should be noted, however, that temperature gradients are complicated by horizontal water flow in the saturated zone, which has not been well defined but is being addressed in USGS-SP 8.3.1.2.3.1.

In 1984, the USGS began two studies designed to measure flux in the upper portion of the unsaturated zone at Yucca Mountain. The objective of the first study was to estimate net-infiltration rates in different surficial materials of Yucca Mountain by monitoring changes in water-content in shallow (<30 m deep) boreholes, used for neutron moisture meter measurements. *Net infiltration* refers to the surface water that has percolated deep enough so that it does not return to the atmosphere by evapotranspiration or by some other flow mechanism. The objective of the second study was to estimate flux in deep nonwelded-tuff units (23 to 122 m deep) by measuring hydrologic parameters on rock core. Both of these studies relied on natural precipitation to supply the water for infiltration and percolation. The present-day arid climate, however, severely limited the type and frequencey of data during potential infiltration events, especially from neutron-access boreholes in surficial units. Preliminary neutron-access borehole data indicate that either intense rainfall occurring in the warmer months or heavy winter snowfall events are needed to generate changes in vertical water-content profiles below 2 m. Only three precipitation events of this nature were recorded on Yucca Mountain between 1984 and March, 1989. Furthermore, these events were very localized, affecting only a small portion of the study area at any one time. Although these data are preliminary results, it should not exclude the possibility of long duration winter rainfall generating fluxes below 2 m.

Because of the limitations of available data, additional approaches are required to characterize present-day infiltration in the unsaturated zone. Artificial-infiltration tests will be done to characterize precipitation and resultant runoff under present-day and simulated wetter climatic conditions and will be used to characterize a variety of possible boundary conditions for Yucca Mountain.

Three major tests have been designed to characterize present and future water flow in the shallow unsaturated zone. They include: (1) the natural-infiltration study, which includes the ongoing monitoring of water content in surficial materials using the neutron moisture meter, (2) an artificial-infiltration study, and (3) a study designed to characterize the physical and hydrologic parameters of surficial materials. The objectives of these activities are to:

1. determine present-day net-infiltration rates (fluxes) in response to natural-precipitation events;

2. determine the range of net-infiltration rates, flow velocities, and flow pathways that can be expected under simulated wetter climatic conditions; and

3. characterize the infiltration-related hydrologic properties for the surficial materials on Yucca Mountain.

Information derived from each of the three activities will be used to.

1. define the upper flux boundary condition;

2. model infiltration rates under varying climatic conditions; and

3. analyze infiltration and related hydrologic data, and group the surficial materials into geohydrologic-surficial units with representative hydrologic properties (Schmidt, 1988).

Methods selected to meet these objectives are based on (1) literature and experience, (2) a multiple approach perspective for a complementary verification to assure success, and (3) prototype testing to finalize selection or modification of methods applicable to Yucca Mountain. Details on the methods and prototype testing can be found in Sections 3.1, 3.2 and 3.3.

### 2.1.2 Parameters and testing strategies

The work planned for this study was developed based on informational needs as defined in the SCP. Hydrologic site parameters* are directly measurable quantities generated by field and laboratory testing; they represent the most basic measurements that will be used to characterize the geohydrology of Yucca Mountain and vicinity. Site parameters are building blocks to support various aspects of the project. Some, such as hydraulic conductivity, support resolution of design and performance issues directly. Others primarily provide bases for analyses and evaluations to be conducted within the geohydrology program or within other characterization programs. Table 2.1-1 lists the site parameters to be obtained from this study.

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*In order to avoid confusion, the term "site parameter" will be used to describe SCP defined "Activity Parameters."

Table 2.1-1. Site parameters derived from this study

| Site parameter | Geohydrologic-unit/structural location |
|---|---|
| **Characterization of hydrologic properties of surficial materials: 8.3.1.2.2.1.1** | |
| *Rock-unit lateral and vertical variability* | |
| Bedrock outcrop | Surficial soils and rocks hydrogeologic and bedrock units |
| Texture | " |
| Thickness of soil and alluvium | " |
| *Rock-unit mineralogy/petrology and physical properties* | |
| Bulk density | Surficial soils and rocks hydrogeologic and bedrock units |
| *Fracture distribution* | |
| Fracture density | Surficial soils and rocks hydrogeologic and bedrock units |
| *Fracture orientation* | |
| Fracture orientation | Surficial soils and rocks hydrogeologic and bedrock units |
| *Surface-water flood and runoff characteristics* | |
| Collection of surficial-materials properties with spectral responses | Surficial soils and rocks hydrogeologic and bedrock units |
| Infiltration-runoff map units | " |

Page 2 Table 2.1-1. Site parameters derived from this study--Continued

| Site parameter | Geohydrologic-unit/structural location |
|---|---|
| **Characterization of hydrologic properties of surficial materials: 8.3.1.2.2.1** | |
| Unsaturated-zone storage properties | |
| Porosity | Surficial soils and rocks hydrogeologic and bedrock units |
| Unsaturated-zone fluid potential | |
| Flow paths | Surficial soils and rocks hydrogeologic and bedrock units |
| Water potential | " |
| Unsaturated-zone moisture conditions | |
| Gravimetric water content | Surficial soils and rocks hydrogeologic and bedrock units |
| Surficial-material water content | " |
| Water-content profiles | " |
| Unsaturated-zone hydrologic conceptual/descriptive models | |
| Spatial variability of hydrologic properties of surficial materials | Surficial soils and rocks hydrogeologic and bedrock units |
| **Evaluation of natural infiltration: 8.3.1.2.2.1.2** | |
| Surface-water flood and runoff characteristics | |
| Rainfall-runoff-infiltration relations | Surficial soils and bedrock exposures |

Page 3 Table 2.1-1. Site parameters derived from this study--Continued

| Site parameter | Geohydrologic-unit/structural location |
| --- | --- |
| **Evaluation of natural infiltration: 8.3.1.2.2.1.2** | |
| Unsaturated-zone fluid potential | |
| Flow pathways | Surficial soils and rocks<br>Hydrogeologic and bedrock units |
| Water-potential profiles | Surficial soils and bedrock exposures |
| Unsaturated-zone moisture conditions | |
| Water-content profiles | Surficial soils and bedrock exposures |
| Unsaturated-zone fluid flux | |
| Evapotranspiration | Surficial soils and bedrock exposures<br>surficial hydrogeologic and bedrock units |
| Infiltration rates, net | Surficial soils and bedrock exposures |
| Infiltration rates, surface | Surficial soils and bedrock exposures<br>surficial hydrogeologic and bedrock units |
| Unsaturated-zone hydrologic conceptual/descriptive models | |
| Spatial variability of natural-infiltration parameters | Surficial soils and rocks<br>Hydrogeologic and bedrock units |

Page 4 Table 2.1-1. Site parameters derived from this study--Continued

| Site parameter | Geohydrologic-unit/structural location |
|---|---|
| **Evaluation of artificial infiltration: 8.3.1.2.2.1.3** | |
| *Rock-unit mineralogy/petrology and physical properties* | |
| Bulk density | Surficial soils and rocks hydrogeologic and bedrock units |
| *Surface-water flood and runoff characteristics* | |
| Rainfall-runoff-infiltration relations | Surficial soils and bedrock exposures |
| *Unsaturated-zone transmissive properties* | |
| Saturated hydraulic conductivity | Surficial soils and bedrock exposures, hydrogeologic and bedrock units |
| Unsaturated hydraulic conductivity | Surficial soils and bedrock exposures hydrogeologic and bedrock units |
| *Unsaturated-zone storage properties* | |
| Porosity | Surficial soils and rocks hydrogeologic and bedrock units |
| *Unsaturated-zone fluid potential* | |
| Flow pathways | Surficial soils and bedrock exposures |
| Water-potential profiles | " |
| *Unsaturated-zone moisture conditions* | |
| Water-content profiles | Surficial soils and rocks hydrogeologic and bedrock units |

Page 5 Table 2.1-1. Site parameters derived from this study--Continued

| Site parameter | Geohydrologic-unit/structural location |
|---|---|
| **Evaluation of artificial infiltration: 8.3.1.2.2.1.5** | |
| Unsaturated-zone fluid flux | |
| Flow velocity | Surficial soils and bedrock exposures |
| Maximum artificial-infiltration rate | " |
| Maximum infiltration rate | " |
| Saturated hydraulic-infiltration rate | " |
| Unsaturated-zone hydrologic conceptual/descriptive models | |
| Spatial variability of artificial-infiltration parameters | Surficial soils and rocks hydrogeologic and bedrock units |

Design and performance parameters represent information required for issue resolution. These parameters can be either directly measurable quantities (such as major-ion water chemistry) or properties derived from other, more directly measurable quantities (such as unsaturated-zone fluid flux). There is no defined one-to-one relationship between a given site parameter and a given design and performance parameter (i.e., a single site parameter may support one or more design and performance parameters, and a single design and performance parameter may be supported by one or more site parameters). The site parameters derived from this study, as a set, should provide information to support the determination of all applicable design and performance parameters (see Table 7.2-1).

Both site design and performance parameters for the geohydrology program are grouped according to parameter categories (SCP, p. 8.3.1.2-10). Parameter categories serve to group similar types of design and performance parameters (supporting design and performance-assessment issues resolutions [SCP Sections 8.3.2-8.3.5]) and match them with groups of site parameters to be obtained during site characterization. Parameter categories were introduced as a classification scheme to relate measurable quantities to specific model components (Figure 2.1-1) that make up the various hydrologic models, from which the principal products of the geohydrology program will be defined.

Even though a conceptual model is currently assumed (SCP Section 8.3.1.1), this study is designed to satisfy the requirements of alternative conceptual models (SCP Table 8.3.1.2-2a) in case the initial assumptions of the current model are found to be invalid. Similarly, while there are conventional theories for fluid flow in soils and in unsaturated, unfractured rock, and flow in saturated, fractured rock, there is not a conventional theory for describing fluid flow in unsaturated, fractured rock. Development of appropriate models for unsaturated fracture flow will be part of Study 8.3.1.2.2.9 (Site unsaturated-zone modeling and synthesis).

Because model parameters cannot be measured explicitly throughout the modeled area, interpolation of parameters between measurement points is necessary. Geostatistical techniques (described in Section 2.1.4) have been identified as the methodology of choice because they allow for flexible consideration of all available data and provide for calculations of variances which aid in estimating the reliability of interpolated values.

Measured and interpolated values for parameters associated with geometry, material properties, boundary conditions, and initial conditions will serve as input to numerical simulators. Calculated variances for each parameter will be used to aid in estimation of expected ranges for sensitivity studies. These numerical simulations will be used as a principal approach to assess the sufficiency of collected data to address performance and design issues.

As described below, however, the strategy of the study is to use multiple approaches for determining parameters which are difficult to measure. (Table 2.1-1 shows that some parameters listed are being

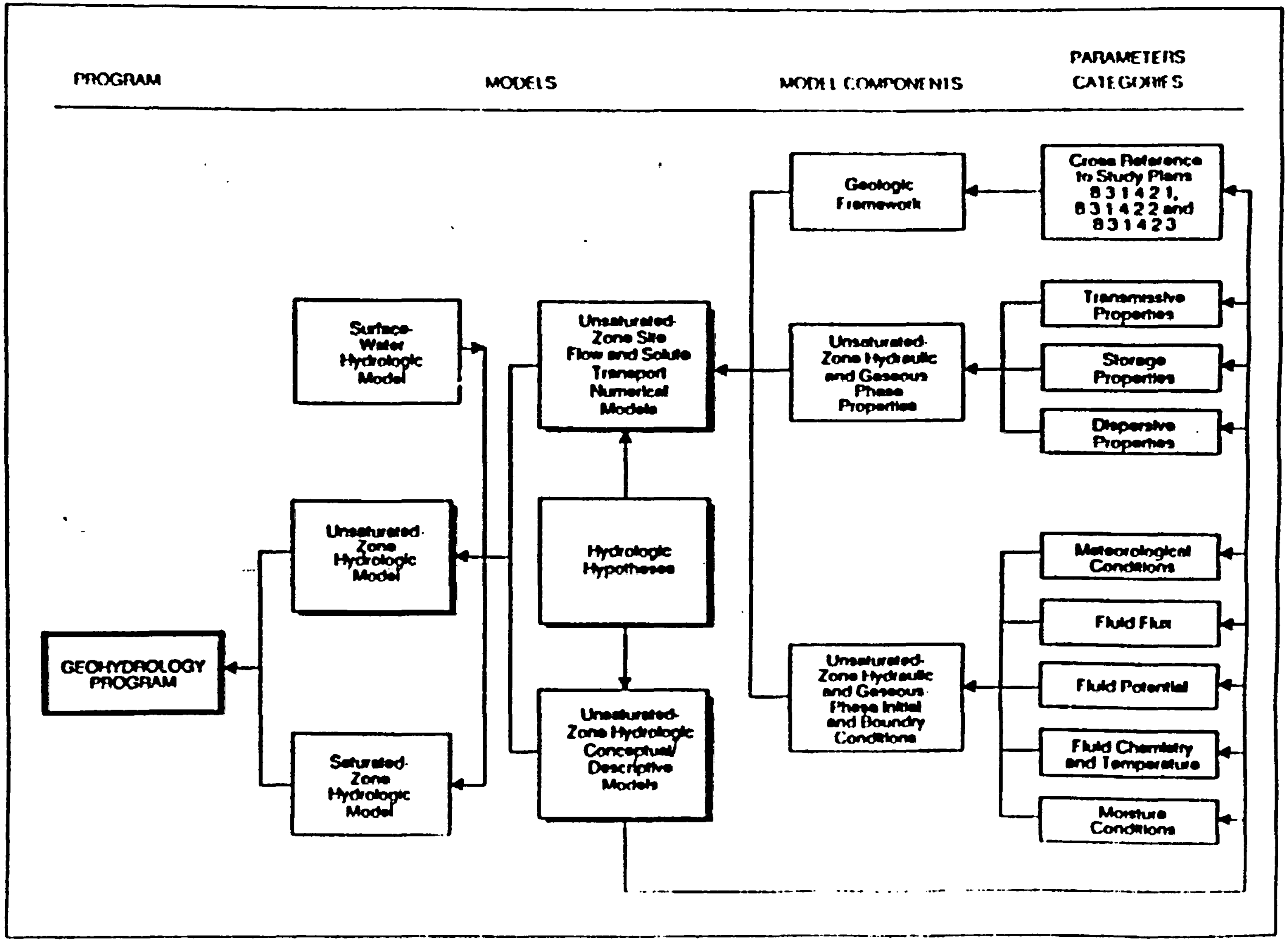


Figure 2.1-1 Logic diagram of geohydrology program including model components and parameter categories

determined by more than one activity (multiple approaches).) There are several advantages to using multiple approaches for determining parameters. First of all, the ability to demonstrate repeatability increases confidence in the data collection procedures. In addition, reliance is not placed on only one test to determine a parameter. Some tests will provide only partial information, whereas others will provide extensive information necessary for determination of a hydrologic parameter. By combining the results of several tests, a greater understanding of the parameter and processes may be achieved. For example, estimates of infiltration rates in the surficial materials, needed as a boundary condition for evaluating deep percolation will be estimated through monitoring of natural infiltration, characterizing hydrologic properties of surficial materials, and conducting various controlled infiltration tests. The information obtained by these tests will be used to reduce uncertainty in the spatial and temporal distribution of measured infiltration rates.

Second, since some of the tests are unproven for the Yucca Mountain environment, there is less confidence in their ability to achieve the desired objectives. An advantage, then, of using multiple approaches is that the failure or the partial failure of one or two of the tests is not likely to severely inhibit the ability to provide the information required.

The third reason for multiple appraoches is the necessity to measure parameters at various scales of interest to assess the influence of different processes operating at different scales on measured values For example, a core-sample measurement of hydraulic conductivity is a function of matrix properties (i.e., interconnected pore space, water content, tortuosity, temperature, etc.), while a field scale test of hydraulic conductivity may be dominantly a function of geologic structure, such as fractures, fault zones, and bedding planes. Measurements of hourly rates of precipitation may show a relatively random characteristic, with some correlation to storm cell size, storm track, duration, wind speed, wind direction, etc., while measurements of annual rates of precipitation may show a strong correlation to ground surface elevation, geographic location and weather patterns.

The influence of each specific correlation must be assessed: (1) to determine the minimum sample dimension needed to provide a usable and valid representation of a given parameter, (2) to determine the minimum sampling density needed to adequately characterize a given parameter over the areal extent of the proposed repository, and (3) to successfully define average values of each parameter over some designated subdomain.

The objective is to obtain an optimum balance between the small scale measurements needed to characterize a parameter with adequate detail, and the large scale measurements needed to estimate average values. A balance is needed because the number and density of measurements needed to characterize a parameter at a small scale over a large domain are usually not obtainable due to: (1) sampling impacts on the site, (2) testing limitations, (3) resource limitations, and (4) time limitations.

Variable-scale tests with different approaches to evaluate identical parameters will delineate specific relations between hydrologic parameters and provide an increased large-scale understanding of the surficial materials covering Yucca Mountain. This multiple-scale, multiple-technique approach will increase the confidence in estimates of infiltration rates in the shallow-unsaturated zone, and in the confidence that appropriate data are being used for modeling and testing each hydrologic hypotheses.

Finally, the sampling scheme will be optimized by providing a sampling network that maximizes spatial coverage, providing a variety of scales, and minimizing estimation variances within the designated boundary. In practice, the sampling network will also depend on: (1) the shape and nature of the boundary defining the domain of interest; (2) the location of existing points of measurement (e.g., existing boreholes); and (3) known anisotropy and/or heterogeneity within the domain of interest.

2.1.3 Hydrologic hypotheses

The following generalized description of the principles of near surface unsaturated zone behavior is included here as a framework for the characterization of surficial materials and infiltration.

The near surface environment of arid and semi-arid areas is a dynamic zone whose hydrologic behavior is a function of physical properties, state variables and external inputs. Inherent physical properties of the surficial materials include elevation, slope, aspect, depth to bedrock, geology, mineralogy, bulk density, porosity, fracture characteristics, heat capacity, water holding capacity, saturated and unsaturated hydraulic conductivity and particle size distribution. State variables include temperature, water content, and water potential. External inputs include precipitation, solar radiation, wind, barometric pressure fluctuations, atmospheric deposition, biotic and mechanical activity.

Precipitation is perhaps the most important parameter to be characterized and evaluated early in the program. Precipitation which falls on Yucca Mountain may take one of four distinct paths: it may (1) be evaporated back into the atmosphere, (2) infiltrate through the soil surface, (3) move laterally as surface runoff, or (4) collect in surface depressions. If the water infiltrates, it may either be held in storage, removed by evaporation, removed by plant transpiration, or moved downward by gravity and capillary forces.

If precipitation rates exceed the infiltration rate of soil surfaces, the water will move laterally, under the gravitational gradient, toward streams channels. Once in the channel, this water may either infiltrate through the channel bed or be discharged from the basin. Transmission losses in ephemeral channels are large due to the high permeability of the sediments and large storage capacity, particularly after extended dry periods. In contrast to basins in humid regions, discharge per unit basin area decreases with increasing basin

size in arid and semi-arid regions. This fact is due to the increasing distance that water must travel to the basin discharge point with increasing basin size, thus increasing the channel residence time and therefore increasing the total amount of infiltration. In addition to permeable sediments in the channel, possible open fractures in the underlying tuffs could serve as infiltration pathways under saturated conditions.

The uplands of Yucca Mountain, where the greatest amounts of precipitation are expected to occur, are characterized by steep slopes, shallow soils, and bedrock outcrops. As a consequence, saturated conditions may exist for short time periods, contributing to movement of water into exposed fractures or fractures under the shallow soils. Water that does not move into fractures or rock matrix can move under the soil at the rock-soil interface along a gravitational gradient toward stream channels. As soil thickness increases, the quantity of water necessary to reach saturation at the rock-soil interface increases. If the water content increases at the rock-soil interface but does not saturate the soil or move into fractures, the water can still be imbibed into the rock matrix, although quite slowly.

During and between precipitation events, evapotranspiration will occur at the soil surface. Evapotranspiration is a function of the available energy, soil resistance to flow, and availability of water (which controls soil resistance to water flow). During the summer, potential evapotranspiration rates are high, reducing the amount of water that may become net infiltration. During the winter, evapotranspiration is reduced due to a lack of available energy. The reduced evapotranspiration in the winter may be more important in leading to net infiltration than the high intensity summer thunderstorms. Water that collects at the rock-soil interface in shallow soil from winter precipitation can either be taken up by fractures or imbibed into the matrix. If the water remains near the surface, it can be removed by evapotranspiration in the spring, even from the rock matrix. If favorable conditions exist, such as deep soils, water can move beyond the zone of evapotranspiration. In this case, water that imbibes into the matrix or moves into fractures will likely become recharge.

Although summer precipitation could behave in a similar manner, it is less likely that water will reach below this zone of evapotranspiration since evapotranspiration is actively occurring immediately after the precipitation event. On an annual basis, however, potential evapotranspiration exceeds precipitation, which emphasizes the need to describe both precipitation and evaporation on a short time scale (i.e., hours or days). The emphasis on knowing the spatial variability of precipitation, evaporation and soil thickness also becomes apparent. The distribution of net infiltration is, then, dependent on the distribution, frequency, intensity and duration of precipitation events, as well as the evapotranspiration following the precipitation events.

## 2.1.4 Hydrological and geostatistical modeling

In assuming that the overall hydrologic system within the unsaturated zone at Yucca Mountain can be described by conventional theories of fluid storage and movement in porous and fractured media, the present and probable-future spatial distribution and values of hydrologic parameters can be estimated from appropriately constructed hydrologic models. The successful development of numerical models of the hydrologic system will increase confidence in the geohydrologic framework, distribution of input parameters, and initial and boundary conditions, and thus increase the confidence in performance and design analyses.

Because the spatial and temporal simulation of moisture flow within the shallow unsaturated zone involves complex interactions that can be described only with the aid of hydrologic models, preliminary data from infiltration tests will be used for multiscale, numerical modeling of the shallow-unsaturated zone. These models will, in turn, contribute to the geohydrologic program of Yucca Mountain that will provide a description of the important components of the geohydrologic system and will reflect an understanding of hydrologic parameters and initial and boundary conditions and processes.

Hydrologic models will be developed to describe two distinct zones of the hydrologic system: the unsaturated zone and the saturated zone (Figure 2.1-1). In turn, the unsaturated-zone system and the upper portion of the saturated-zone system on Yucca Mountain are divided into three activities to facilitate site characterization. The zone of surface infiltration is the subject of this study plan. A very thick unsaturated zone of percolation is located immediately beneath the zone of infiltration (Studies 8.3.1.2.2.3 and 8.3.1.2.2.4), and the zone of percolation is underlain by the saturated zone (Study 8.3.1.2.3.1). Data from each of these zones will be used in formulating the unsaturated- and saturated-zone models. In addition, a surface-water hydrologic model (Study 8.3.1.2.1.2) will be developed to provide input to the other two hydrologic models, as they are also impacted by surface water.

The hydrologic models will be used at many stages to perform preliminary analyses, to design and analyze tests and experiments, and to analyze and interpret field data. Experimental data may have uncertainties due to measurement errors and to the presence of both random and correlated large-scale spatial variability (heterogeneities). These uncertainties must be considered to assess the accuracy with which numerical hydrologic models can simulate the natural geohydrologic system. The sensitivity of performance measures (Table 7.2-1) to various parameters will be determined. Models can be used as tools to improve understanding of the geohydrologic system, to test hypotheses, and to further guide data collection.

Preliminary conceptual models of the unsaturated-zone hydrologic system were developed by Montazer and Wilson (1984), Klavetter and Peters (1986), and Wang and Narasimhan (1985). These models were based on principles of unsaturated flow, some preliminary data, and a basic

knowledge of the geologic framework at Yucca Mountain. Several discussions exist throughout the text of how this study will provide data necessary to test conceptual models. Data to be collected in this study are necessary to test the validity of these models as well as alternative conceptual models.

The infiltration tests and corresponding hydrologic models in this study plan concentrate on the shallow unsaturated zone. Data from the infiltration studies will be used to determine if flow pathways and fluxes agree with those assumed by conceptual model. These data will not only contribute to an understanding of the present climatic conditions, but will be useful in understanding the infiltration process for future, possibly wetter climatic conditions. In turn, this understanding of the infiltration process for various conditions will be used in the development and validation of numerical models for alternative climatic scenarios (see Section 4 for appropriate references). Finally, implementation of these models will result in determination of the upper flux boundary conditions of surficial materials at Yucca Mountain, essential knowledge for modeling flux through the entire thickness of the unsaturated zone.

Results from hydrologic modeling may be used to analyze the flow field for defining flow paths and computing ground-water travel time. Such modeling requires sufficiently detailed knowledge of the hydrogeologic framework and the distribution of hydrologic parameters. The unsaturated-zone hydrologic model, which is an integral part of the geohydrologic program, will use hydrologic parameters determined by the infiltration tests. The importance of the unsaturated-zone infiltration tests for determining the values and distribution of hydrologic parameters is emphasized. Multiple-approach, variable-scale testing of surficial materials, and geostatistical analysis of infiltration-related parameters will enhance the data base necessary to understand the upper boundary conditions for water movement in the unsaturated zone. Ultimately, this will lead to the complete development of an unsaturated-zone model and to the increased understanding of the repository block beneath Yucca Mountain.

Geostatistics will be used in interpolation of values of parameters for areas where measurements are not available, and allow for calculation of variances which may aid in estimation of reliability of interpolated values. Water content, conductivity, depth to bedrock, thickness of unsaturated zone, precipitation, potential evapotranspiration and ground slope are examples of parameters that may be amenable to geostatistical analysis. It is specifically noted that geostatistical methods are being used primarily as a method of interpreting data and will not be utilized as a replacement for deterministic approaches or as a basis for quantification of uncertainties.

Geostatistical methods refer to a collection of statistical techniques for analyzing and modeling the spatial structure of "regionalized variables" distributed spatially and/or temporarily. These techniques are based on the "Theory of Regionalized Variables" developed by Matheron (1963), whose work provided the theoretical basis

for the methodology originally developed by Krige, Sichel, and de Wijs in the 1950's to estimate ore reserves in the gold fields of South Africa (Clark, 1979; David, 1977; Henley, 1981). A geostatistical analysis can be used to: (1) estimate values of the regionalized variable at unmeasured locations (or times) within a vector space; (2) calculate estimation variances for estimated values; and (3) help identify optimum sampling locations for additional measurements of a regionalized variable.

Geostatistical techniques were selected over other estimation schemes because they are believed to provide the best (minimum estimation variance) linear unbiased estimate of a regionalized variable. This is achieved by the use of a covariance or semivariogram model, which defines the spatial correlation structure of a regionalized variable. The estimate is a linear combination of available measurements, and the vector of "weights" is obtained by solving a system of linear equations. The system of equations incorporates information about the relative distance and direction of the available data to the point being estimated, and the configuration of each data point relative to all other data points used in the estimation. The weighting vector is also used to calculate the estimation variance of the estimated value.

Multivariate techniques can be utilized to characterize and model spatial cross-correlations between regionalized variables. This allows for the incorporation of measured values of all correlated variables into the estimation of a variable at unmeasured locations, and results in reduced estimation variances (improved estimation accuracy). The amount of improvement is dependent on: (1) the degree of correlation between variables; (2) the proximity of additional data to the point being estimated; (3) the arrangement of additional data in relation to the point being estimated; (4) the number of additional data used in the estimation; and (5) the arrangement of the additional data with respect to the measured values of the variable being estimated.

The analysis of the random component of a regionalized variable involves the use of the experimental semivariogram, which is derived from the available data. The structure of spatial variability can be determined by careful inspection of the experimental semivariogram, in conjunction with a careful inspection of the spatial configuration and distribution of measured values, and knowledge of the physical nature of the regionalized variable. If sufficient data are available, directional experimental semivariograms, as well as "local" experimental semivariograms within various subsets of the total sample can be calculated. This allows for a more detailed structural analysis in which assumptions about isotropy and stationarity of the regionalized variable can be tested.

Using the results of structural analysis, model semivariograms are selected and fitted to the experimental semivariograms. The models can include: the range of spatial correlation, the degree of spatial correlation, the "nested" spatial structures associated with different scales, directions of maximum and minimum variability (zonal anisotropism), proportional effects associated with non-stationarity.

directional changes in the range of spatial correlation (geometric anisotropism), the range of quasi-stationarity, etc. The validity of the fitted model can be tested using cross-validation in which each measured value is individually removed and estimated using the remaining values. A comparison of the measured and estimated values gives a measure of the validity of the model.

Therefore, it is important that the model of spatial structure reflect geologic reality, and these procedures can be modified to incorporate qualitative or subjective information (so-called "soft" data). Through the use of techniques such as soft kriging, interval kriging, and Bayesian kriging, the estimates and estimation variances can be constrained to reflect soft data (e.g., prior knowledge of geologic structure and stratigraphy). With these processes, the most accurate and realistic estimates may be obtained.

## 2.2 Constraints on the study

### 2.2.1 Representativeness of repository scale and correlation to repository conditions

The unsaturated-zone infiltration tests will be performed at sites on Yucca Mountain and overlying the repository block. Because of this, the environment in which the infiltration tests will be conducted is representative of the repository area. How well each test will represent present or future conditions of the repository area at the scale of the repository depends on factors particular to each test.

### 2.2.2 Accuracy and precision of methods

Selected and alternate field tests are summarized in tables at the end of each activity description (Section 3). These tests were selected on the basis of their expected precision and accuracy, duration, and interference with other tests and analyses. The actual accuracy and precision of the surficial-hydrologic and infiltration-properties tests is difficult to quantify prior to any implementation of testing.

### 2.2.3 Potential impacts of activities on the site

The tests described in this plan are not expected to impact the repository block site conditions, nor have adverse effect on the ability of Yucca Mountain to isolate waste. The proposed work should not affect the site in terms of either exploratory shaft or repository design. Approximately 100 neutron-access boreholes for site characterization and monitoring natural infiltration will be drilled in the surficial units. These boreholes will only penetrate several meters into the bedrock and will not penetrate the repository block. The construction of rainfall-simulation plots will impact only a small area of the ground surface and have no impact on the repository block. The small amount of water supplied to the surface (<30 cm) is equivalent to one or two years of precipitation. The rainfall simulations are designed to cause runoff so that the majority of water applied is later collected and measured.

### 2.2.4 Time required versus time available

A tentative schedule of work activities and reports is given for the three activities in Section 5. These schedules assume that five years will be available for site characterization. The start of the natural- and artificial-infiltration activities is constrained by the construction of the rainfall-simulation plots. The drilling of neutron-access holes is not considered to be a major constraint on the timing of this study. Also, the time required to complete each test and analyze the data will not be a constraint.

### 2.2.5 Interference

There are no known interferences between this study and other studies within the site-characterization plan, nor will the proposed work interfere with the design and construction of the exploratory shaft facility.

# 3 DESCRIPTION OF ACTIVITIES

The study is organized into three activities:

- 8.3.1.2.2.1.1 - Characterization of hydrologic properties of surficial materials,
- 8.3.1.2.2.1.2 - Evaluation of natural infiltration, and
- 8.3.1.2.2.1.3 - Evaluation of artificial infiltration.

The plans for these activities are described in Section 3.1, 3.2, and 3.3, respectively.

## 3.1 Characterization of hydrologic properties of surficial materials

### 3.1.1 Objective

The objective of this activity is to characterize the infiltration-related hydrologic properties of the surficial materials covering Yucca Mountain.

### 3.1.2 Rationale for activity selection

Hydrologic-property data from the surficial materials of Yucca Mountain are required to calculate or model ground-water flux and to define geohydrologic-surficial units. In this activity, hydrologic properties are defined to include parameters which are properties of the soil and rock or the soil-rock-fluid system: density, porosity, permeability, water characteristic curves, soil texture and fracture characteristics. They also include parameters which describe the *in situ* hydrologic condition, or state of water, in the soil and rock: water content, water potential, and matric potential. Many of the methods that will be used to determine these parameters (listed in Table 3.1-2, p. 3.1-28) are discussed in detail in Study 8.3.1.2.2.3 (Characterization of percolation in the unsaturated zone -- surface-based study). Present-day fluxes at point locations can be estimated using Darcy's Law, or equations based on Darcy's Law, that incorporate water potentials, moisture content, and permeability (saturated or unsaturated), measured at these locations.

For both conceptual and mathematical modeling, Yucca Mountain may be divided into large areas called geohydrologic-surficial units, each characterized by a set of unique hydrologic properties. A statistically based, matrix hydrologic-testing program for soil and rock samples complemented by a similarly designed *in situ* or field-based hydrologic-parameter testing program is necessary to characterize the spatial distribution of hydrologic parameters for all of Yucca Mountain. Statistical and geostatistical methods will be used to analyze hydrologic data and to estimate parameters between measurement points. These analyses and estimates will then be used to identify boundaries between geohydrologic-surficial map units and to calculate flux within the units.

As mentioned above, hydrologic-property data will be obtained both from laboratory measurements on soil and rock samples and from *in situ* or field measurements. Measurements on soil and rock samples will be limited to matrix-hydrologic properties. Field measurements will include both matrix and fracture properties. (Fractures will also be addressed and supporting data collected in Sections 3.3.3.1, 3.3.3.3, 3.3.3.4 and USGS-SP 8.3.1.2.2.8 and SP 8.3.1.2.2.9.) Rock samples will be collected mainly as core from neutron-access and infiltration-related boreholes and from outcrops. Soil samples will be obtained from the surface of Yucca Mountain as grab samples or minimally disturbed core. Procedures for analyzing core as well as determining numbers of core samples and distance between samples are in Study 8.3.1.2.2.3. *In situ* measurements of hydrologic properties, as well as soil sampling and testing, are in Section 3.1.3. It is currently not feasible to identify

*a priori* the number and location of all samples. Since this study uses multiple approaches and is iterative, sufficient samples will be collected for characterization of surficial materials.

3.1.3 General approach and summary of tests and analyses

Characterization of the hydrologic properties of surficial materials includes: (1) sampling, testing, and mapping; (2) borehole geophysical investigations; (3) surface geophysical investigations; (4) remote sensing; and (5) geostatistical analysis. Analyses done on core collected from the boreholes, as outlined in USGS-SP 8.3.1.2.2.3, will be used to support these studies. Hydrologic characteristics from these and other tests described in this plan will be analyzed using statistical and geostatistical methods to delineate geohydrologic-surficial units. Representative hydrologic characteristics for areally subdivided geohydrologic surficial units will then be used to model infiltration at Yucca Mountain.

Geohydrologic-surficial units which are initially defined on the basis of shallow-infiltration behavior of the upper 0.3 m (1 ft) of surficial material are called *infiltration-runoff map units*, which may include more than one stratigraphic unit (0.3 m is the depth of investigation for most of the surficial tests, i.e., bulk density samples and infiltrometer). Infiltration-runoff map units encompass the plant-soil-atmosphere boundary. It is for these surface units that the calculation of infiltration and runoff rates will be made. These units are expected to include the influence of surface hydrology, including plant cover, litter cover, and biotic activity, as well as atmospheric inputs such as precipitation, wind and shortwave and longwave radiation. In addition, the processes of heat and vapor transfer through the soil and plants are most dynamic in the upper 0.3 m of soil and can be readily characterized in that location.

Geohydrologic-surficial units which are defined to characterize net infiltration processes at depths greater than 0.3 m are termed *geohydrologic-surficial map units*. Interfaces between soil cover and bedrock are contained in these units. Infiltration tests are expected to help define the direction and magnitude of water movement beneath the active root zone, below which the short time constant atmospheric inputs are largely dampened. The depth below which infiltration continues down to become recharge is contained within these units, and definition of this depth range is an important objective of this study. It is recognized that in some cases infiltration-runoff map units and geohydrologic-surficial map units may be congruent.

Figure 3.1-1 summarizes the organization of the surficial-materials tests. A descriptive heading for each test and analysis appears in the boxes of the second row. Below each test/analysis are the individual methods that will be utilized. Figure 3.1-2 summarizes the objectives of the activity, design- and performance-parameter categories which are addressed by the activity, and the site parameters measured during testing. These appear in the boxes in the top left side, top right side, and below the test/analysis boxes, respectively, in Figure 3.1-2.

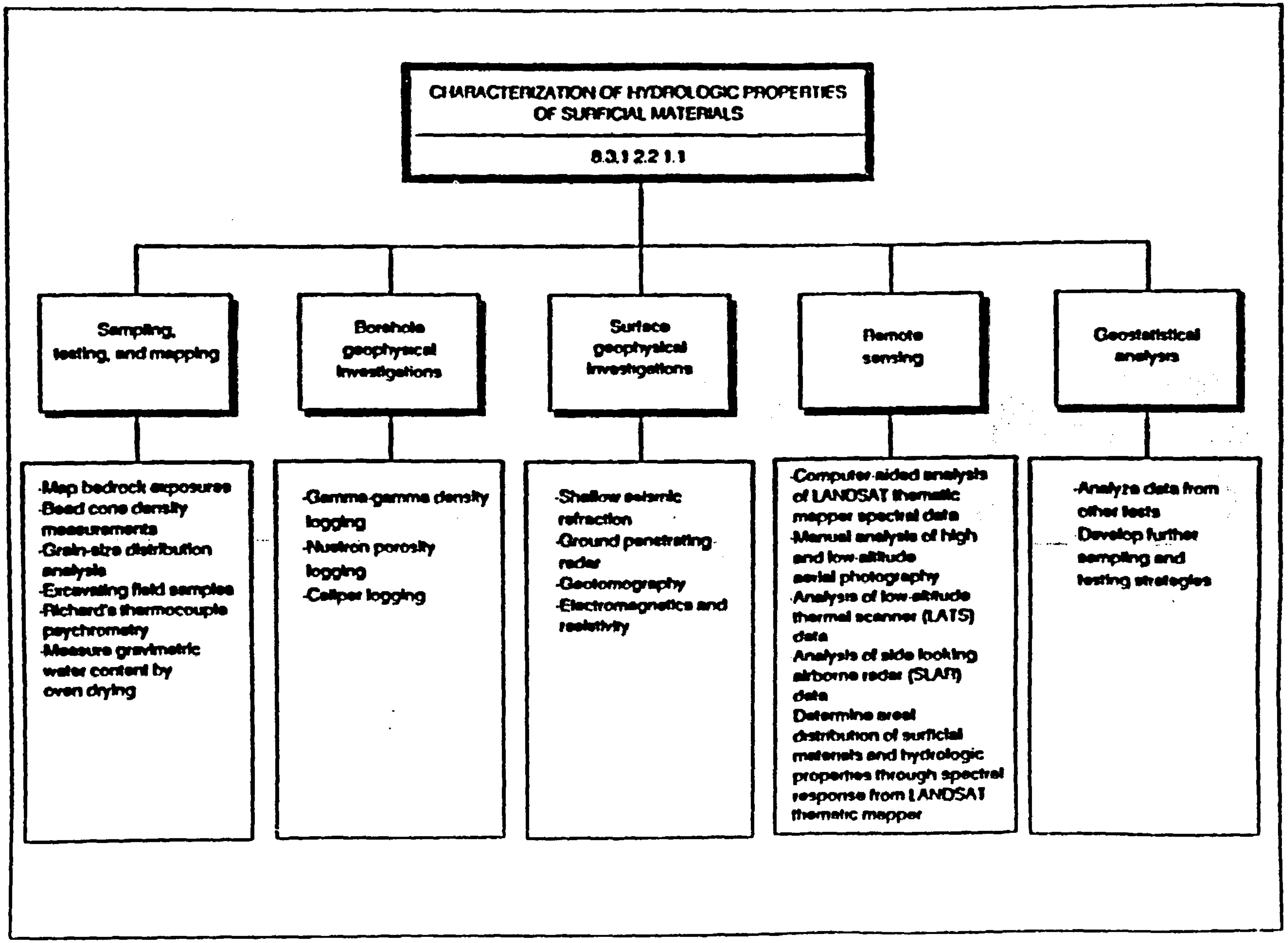


Figure 3.1-1 Logic diagram for hydrologic properties of surficial material showing tests, analyses, and methods

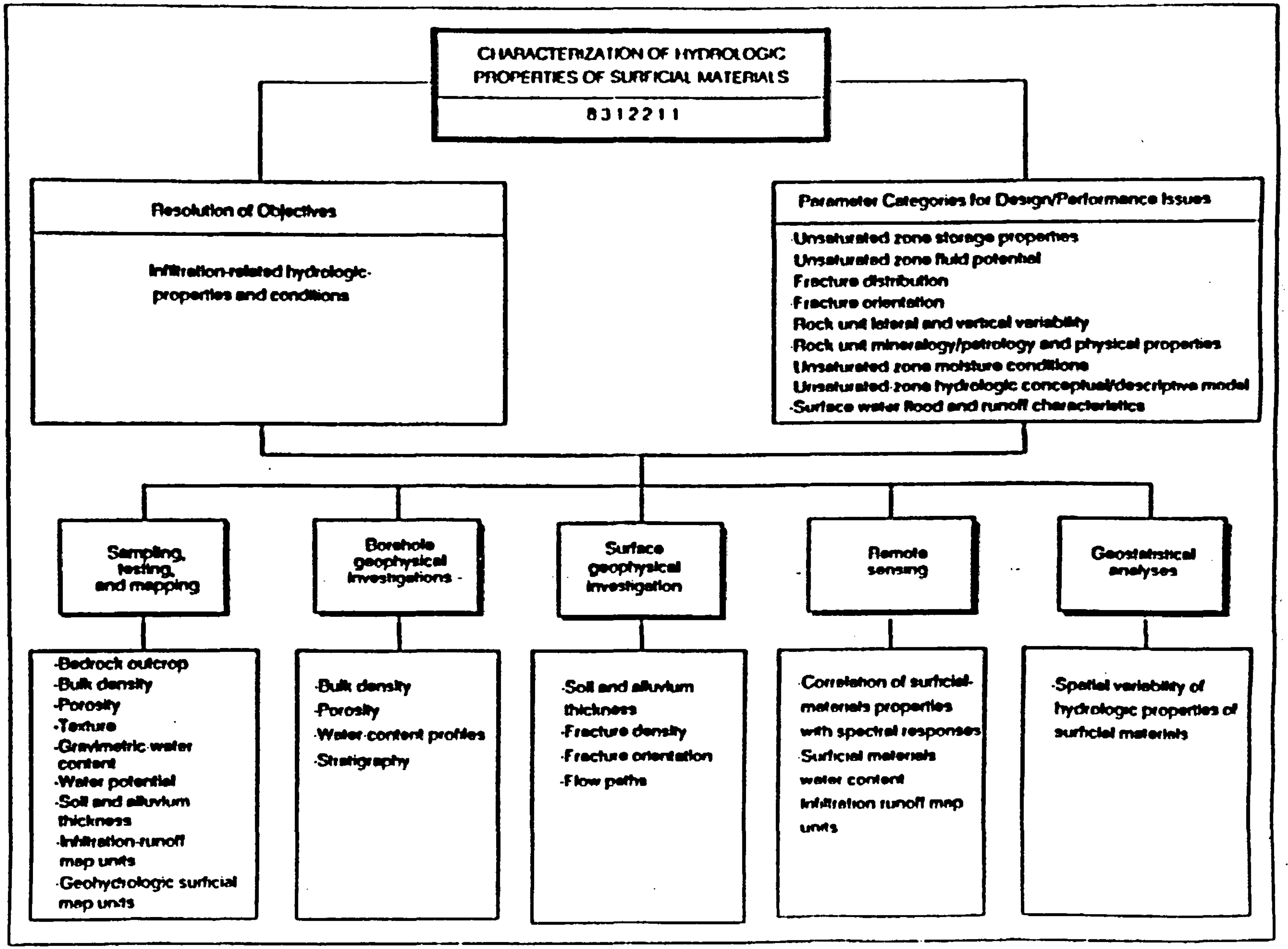


Figure 3.1-2. Logic diagram for hydrologic properti-- of surficial material showing tests, analyses, an- ... ite ... meters.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the site parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The following sections describe tests and analyses to be conducted as a part of the surficial-materials tests. Each of the tests described in these sections has been divided into prototype and site-characterization components. The prototype component must be successfully completed before the site-characterization component can begin. Characterization of the site with these methods will not be conducted if prototype tests indicate that methods and/or equipment cannot be successfully applied to Yucca Mountain.

Hydrologic-properties tests will consist of extensive sampling and hydrologic characterization of surficial materials of Yucca Mountain overlying the repository block. Geostatistical analyses are planned to assess the spatial (lateral) variability of surficial hydrologic characteristics. Modeling these lateral variabilities in conjunction with vertical distributions of parameters (evaluated from other activities) will result in a three-dimensional distribution of the values and variabilities of parameters within the repository area. Similarly, representation of present conditions will be useful for modeling and predicting potential future repository conditions.

Yucca Mountain is centrally located in the Amargosa Basin drainage (Figure 3.1-3). All drainage on and around Yucca Mountain have a common outflow point at the south end of the basin. This basin is the framework for the regional meteorology studies (Study 8.3.1.2.1.1) and will be described in that study plan. The repository boundary is overlaid by three distinct watersheds shown in Figure 3.1-4, where the stippled area is the watershed boundaries from Figure 3.1-3 which have been defined using examination of topographic maps and site visits and are proposed as a starting point for further analysis. The three watersheds, Drill Hole Wash, Busted Butte and Solitario Canyon will receive the most emphasis. A fourth watershed, Yucca Wash, will also be considered because of its proximity to the repository block, but will not be described with the same detail. A fifth watershed, Forty-mile Wash, will be considered because of its potential importance to ground-water recharge at the site. Other studies in Forty-Mile Wash are covered under other study plans, Study 8.3.1.2.1.3 (Characterization of the regional ground-water flow system) and Study 8.3.1.2.1.1 (Characterization of the meteorology for regional hydrology).

#### 3.1.3.1 Sampling, testing, and mapping

The purpose of this activity is to develop a map of surficial materials of Yucca Mountain delineating areas or map units with common shallow-infiltration and runoff properties. These map units

AMARGOSA BASIN: DRAINAGE BOUNDARY AND GEOGRAPHY

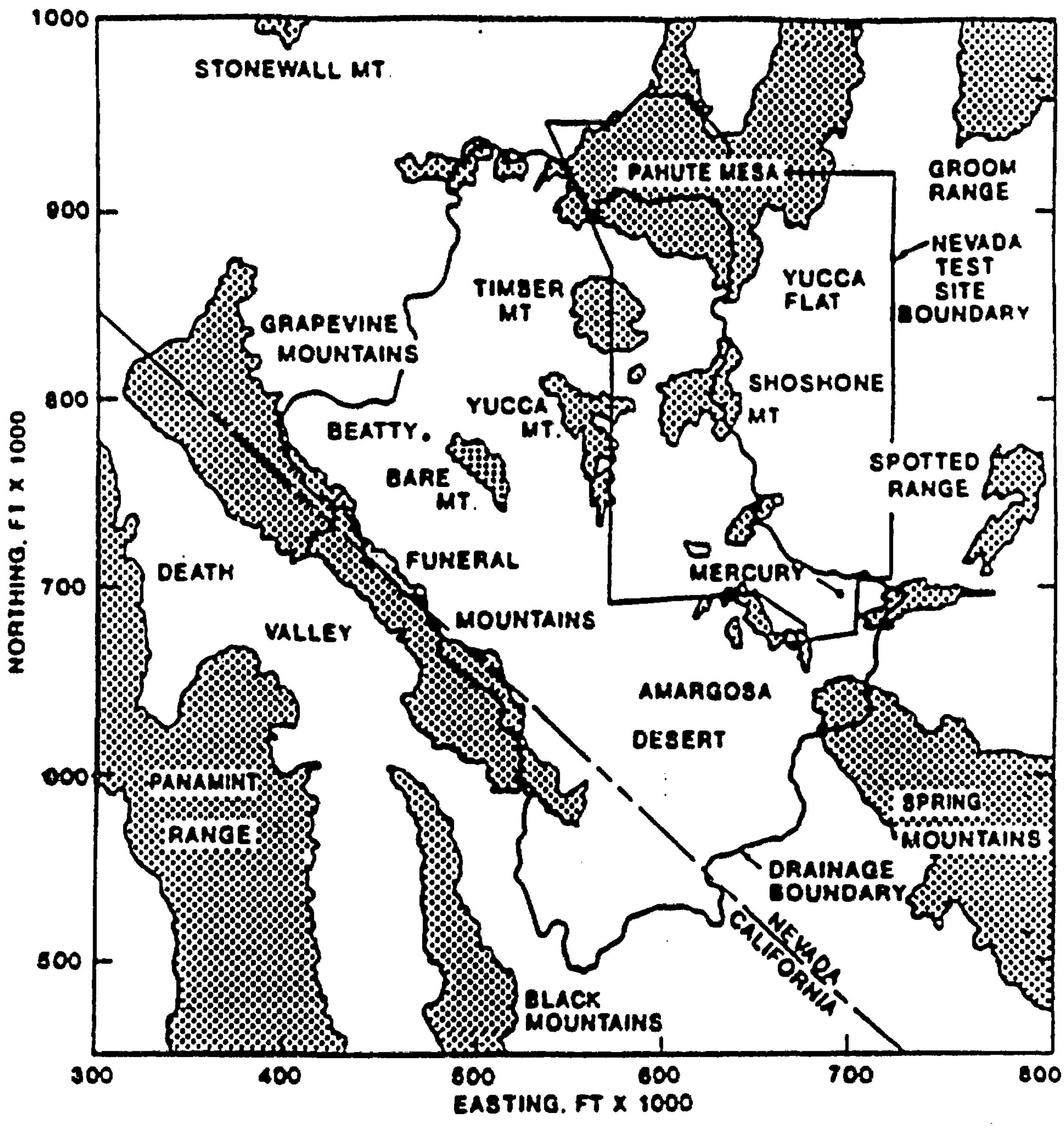


Figure 3.1-3. Map showing boundary and geography of Amargosa Basin, including Yucca Mountain and Nevada Test boundaries. (Nevada Central State Plane Coordinates)

YUCCA MOUNTAIN AND DRAINAGE BOUNDARIES

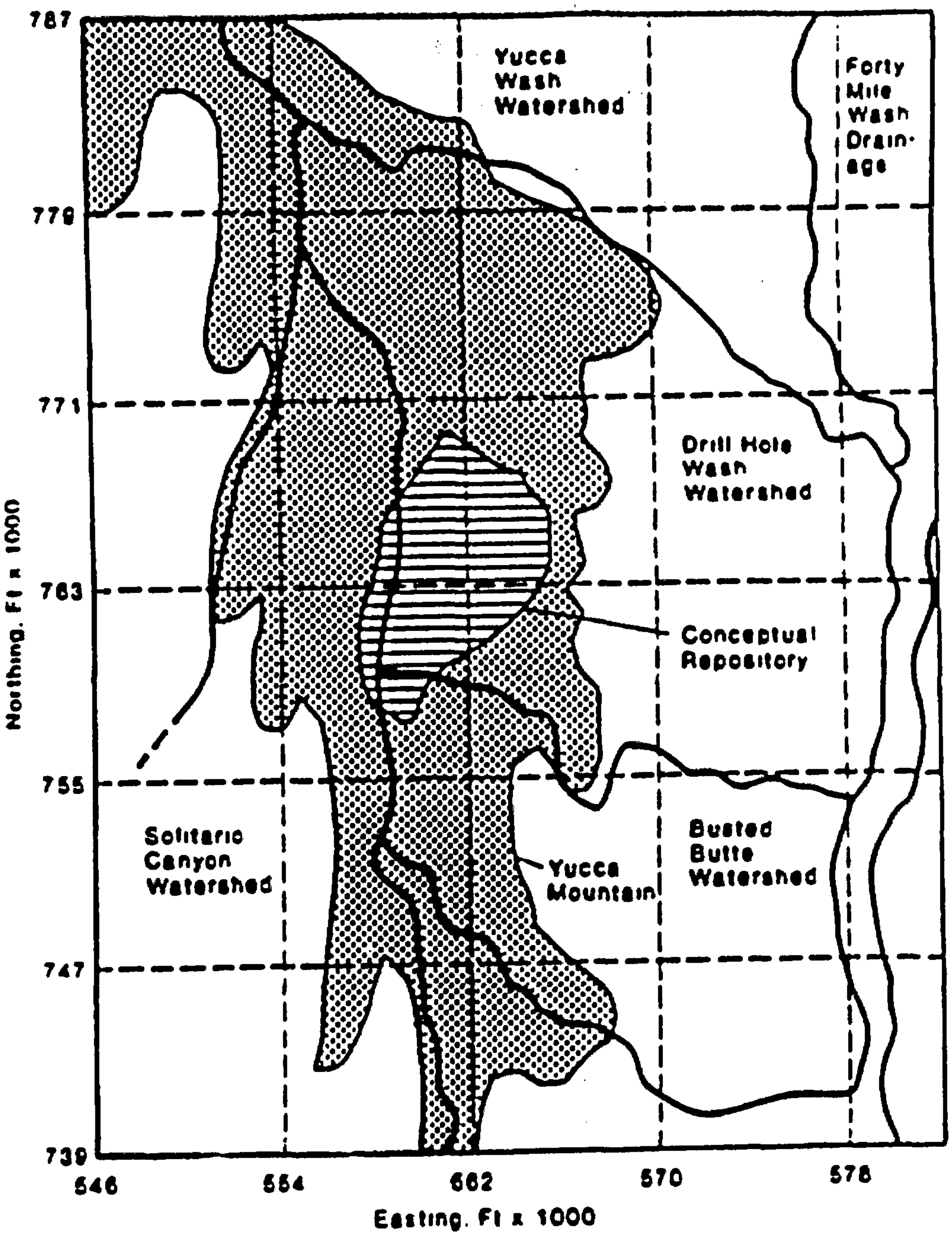


Figure 3.1-4 Map showing drainage boundaries for 5 drainages on Yucca Mountain (Nevada Central State Plane Coordinates)

will aid in modeling runoff and shallow infiltration as a function of precipitation as well as facilitate a quality sampling scheme. The USGS Geologic Division has produced a 1:12,000 geologic map of the surficial materials of Yucca Mountain (Scott and Bonk, 1984). These units are expected to be the base for developing map units with common infiltration and runoff properties.

Geologic-surficial units, defined by Scott and Bonk (1984) will initially be used to develop a sampling and testing scheme to characterize the spatial variability of hydrologic properties. Statistical and geostatistical analyses will be used to help determine the spatial structure of these properties and therefore help to further define infiltration and runoff map units (units which have similar infiltration and runoff properties). As discussed earlier, they differ from the geohydrologic-surficial map units, because the geohydrologic-surficial map units will be defined on the basis of net infiltration while infiltration-runoff surficial map units will be defined on the basis of shallow-infiltration properties of the upper 0.3 m of surficial materials. The relation between geohydrologic-surficial map units and infiltration-runoff surficial map units will be discussed further in Section 3.3.3.1.

#### 3.1.3.1.1 Prototype studies

Prototype sampling, testing, and mapping was done on a canyon-ridge system at Yucca Mountain (Schmidt, 1988). The technical approach focused on relationships among geomorphic process/response systems and the physical properties of surficial materials. The physical properties measured included particle-size distribution, total soil density, fine (<2 mm) soil density and water content. Geomorphic parameters included component landforms, slope, aspect, depositional processes, thickness of surficial material, and particle-size distribution with depth.

During the sampling phase of the work, three different bulk-density samplers were utilized and compared for effectiveness in measuring bulk density and collecting representative soil samples on Yucca Mountain surficial deposits. These were: (1) nuclear-density gage sampler (ASTM, 1984a), (2) sand-cone irregular-hole bulk density sampler (ASTM, 1984b), and (3) bead-cone irregular-hole bulk density sampler (Flint and Childs, 1984b). Due to the high rock-fragment content and rugged topography, the bead-cone irregular-hole bulk density sampler proved more effective in determining bulk density (25-30 cm deep). Irregular hole bulk density samplers are used to measure the volume of an excavated hole. The bead cone fills the hole with a known volume of beads. As this sampler incorporated a larger sample size, it could better represent the variability due to rock fragments. Its design also allowed for use on sloping surfaces. Samples collected from the bead cone excavation were used to determine total and fine soil density, volumetric-water content, water potential, particle size distribution, soil-moisture characteristic curves, and porosity.

The measurements are being used in regression and geostatistical analysis, as well as determining other parameters, such as calculating saturated and unsaturated hydraulic conductivity from particle size distribution (Campbell, 1985).

Additional measurements will be taken in the canyon-ridge system to complement the prototype infiltrometer measurements described in Section 3.3.3.1.1. The results of these measurements will be combined with the prototype tests described in this section to: (1) develop a statistically based sampling program to characterize infiltration-runoff surficial map units; (2) develop a map of infiltration-runoff surficial units in the prototype canyon-ridge system (classification based primarily on geomorphic criteria); and (3) determine if these geomorphically-based surficial map units can be used to delineate infiltration-runoff map units on an areal basis. The resulting surficial maps will also be used to aid in remote sensing studies (Section 3.1.3.4).

The preliminary definitions of infiltration-runoff map units will then be used to define a sampling scheme for conducting prototype infiltration tests in the field. During these tests various infiltrometers will be evaluated (Section 3.3.3.1). The site of each infiltration test will be characterized by determining slope, aspect, vegetation type, percent cover, general soil classification and depth of surficial materials to bedrock. Bead-cone measurements will also be collected at these locations to fully describe the physical properties mentioned earlier.

When all field and laboratory tests and classifications are completed, data bases will be prepared using a geographic information system. Map overlays for each parameter will be prepared. Data from other investigations, both within and external to the scope of this study, will also be incorporated in the database. The final composite will include overlays of infiltration rate, geology, soil physical characteristics, elevation, slope, aspect, *in situ* water content and water potential, soil depth, soil classification, vegetation type and percent cover, remotely-sensed band ratio images, and roads and disturbed areas. These overlays will be combined and analyzed to obtain the composites of parameters that best correlate with infiltration rate. Geostatistical analyses will then be done on the correlated parameters to define the nature of the correlation and to produce estimates of infiltration for each watershed. The estimates will be validated by additional field measurements of infiltration according to Section 3.3.

3.1.3.1.2 Site characterization

An objective of the prototype tests is to develop optimum methods for determining infiltration-runoff units on Yucca Mountain. After optimum methods are identified, technical procedures will be written for detailed sampling and mapping for

Yucca Mountain and surrounding areas. It is expected that a combination of measurements and models will be used to define these units.

### 3.1.3.2 Borehole geophysical investigations

Borehole geophysics is a useful technique that produces continuous records of various earth properties over the length of the borehole. Borehole geophysical logs have several advantages over core samples, such as: (1) they measure a large volume of rock, (2) they are continuous measurements (as opposed to point samples), (3) they are non-destructive, and (4) they can monitor changes in physical properties with respect to time.

#### 3.1.3.2.1 Borehole-geophysical methods

Three types of borehole logs will be done on Yucca Mountain to characterize the hydrologic properties of surficial materials. These are gamma-gamma density logs, neutron-porosity logs, and caliper logs. The small, hand-held, neutron-moisture meters are also used as part of the natural-infiltration studies (Section 3.2).

##### 3.1.3.2.1.1 Gamma-gamma density logging

Gamma-gamma density tools measure wet bulk densities in a formation which is penetrated by a borehole. The tools have a gamma-emitting radioactive source and one or two gamma detectors at different distances from the source. The count rate detected is related to the density of the medium surrounding the tool. A two-detector density tool has the advantage that each detector measures gamma radiation that has traveled through a different volume of rock. The count rates from these different volumes of rock may then be used to identify and correct for apparent density fluctuations caused by changes in borehole rugosity.

##### 3.1.3.2.1.2 Neutron-porosity logging

Long- and short-spaced neutron porosity tools are used to measure volumetric-water content in a formation penetrated by a borehole. When used in conjunction with a density tool, one can infer or calculate dry bulk density of the surrounding rock (Asquith and Gibson, 1982). These tools have a neutron emitting radioactive source and one or two neutron detectors, also at different distances from the source. The neutron count rate in these detectors is primarily influenced by the hydrogen content (primarily in water molecules) of the medium surrounding the tool. A two-detector neutron tool has the advantage that each detector measures neutrons which have traveled through a different volume of rock. The count rates from these different volumes of rock may then be used to identify and possibly

correct for apparent water content fluctuations caused by borehole rugosity.

The short-spaced neutron-porosity tool (that used in the neutron-logging program, Section 3.2.3.1) is very similar to the long-spaced tool in design, but it uses a very short source-detector spacing. This reduction in spacing allows it to achieve much greater vertical resolution, but also reduces the lateral depth of penetration into the formation. Therefore, measurements will be influenced much more heavily by borehole conditions. The long-spaced neutron-porosity tools will be used in conjuction with the short-spaced tool to allow corrections to be made for borehole condition while maintaining a greater vertical resolution.

3.1.3.2.1.3 Caliper logging

Caliper logging measures variations in the diameter of uncased boreholes. It is necessary to run caliper logs in uncased sections of boreholes to describe the rugosity of the borehole in detail. The rugosity information is critical to correctly interpret the previously mentioned geophysical logs, (e.g., in a gamma-gamma density log, high borehole rugosity could be misinterpreted as low wet bulk density in the formation).

3.1.3.2.2 Calibration of borehole geophysical tools

Before results from borehole geophysical tools can be used quantitatively, it is first necessary that they be properly calibrated. Tool calibration is dependent on many factors including tool design, hole conditions, casing type, hole diameter and rock properties. Both laboratory and field calibrations will be used. The field calibration equation will be transferred to laboratory standards as a long-term, non-changing reference, as discussed in the following section. Borehole calibrations, based on comparing tool response to measurements on core samples, will be used as the principle method for calibrating logging tools.

3.1.3.2.2.1 Laboratory calibrations

Laboratory calibration for the nuclear logging tools will consist of three categories: (1) field calibration, (2) secondary laboratory standards, and (3) portable field standards.

Two continuously cored boreholes will be used as field calibration reference holes. Core collected will be processed in the laboratory to determine bulk density, porosity and volumetric water content. Neutron moisture meters will be used to log the calibration boreholes immediately upon completion of coring. Correlation between laboratory measurements and field measurements will

constitute a field calibration. Since the field conditions are expected to change, the neutron-moisture meters will be logged in the nonchanging secondary standards to carry forward the field calibration in time. The secondary standard (described below) will be used to verify any new neutron moisture meters and periodically (every 6 months), all active neutron moisture meters.

The secondary laboratory standards (basically, tanks filled with a material of known density and water content) are designed so that nuclear logging tools will have a similar response to actual field conditions. The tanks are large enough to be considered "infinite" (i.e., the tool is not influenced by the presence of the boundaries of the calibration standard) and contain the same type of casing used in the neutron access holes. The material in the tanks is selected to have similar mineralogy, water content and density as the field and this makes them very useful for optimizing tool design. These standards also provide a reference which may be logged on a routine basis to guarantee tool stability.

Three of these tanks have already been constructed. They contain a mixture (equal parts by weight) of fine, natural sand and 200-mesh silica flour. The volumetric-water contents of these tanks are 20.7%, 13.8% and 7.7% (Table 3.1-1). Two more calibration tanks have been proposed, one with saturated silica sand (with a porosity of about 35%), the other with a sand-silica flour mixture having a very low water content (approximately 0.5%). After five years of monitoring, no redistribution of water in the tanks has been observed.

Calibration standards for gamma-gamma density probes will also be constructed. The current calibration tanks (with a dry bulk density range of 1.5-1.6 g/cm$^3$) do not have the necessary range of density values (Table 3.1-1) to construct useful calibration curves. The new standards will be constructed from large blocks of aluminum, magnesium, and sulfur using the same borehole diameter as used in the calibration tanks (128 mm ODEX casing).

The third category, portable field standards, insures that the tools are functioning properly before and after they are used on a daily basis. The standards are, typically, small aluminum or magnesium blocks. Two standards of differing densities are used so that the calibration may be tested for changes in both displacement and slope.

3.1.3.2.2.2 Field calibrations

Because laboratory calibrations cannot reproduce field conditions exactly, proper borehole-field calibrations are

Table 3.1-1. Density and water-content data from shelby tube samples for current calibration tanks (SCP 8.3.1.2.2.1.1)

[$g/cm^3$, grams per cubic centimeter; $cm^3/cm^3$; cubic centimeter per cubic centimeter]

| Simulator number | Number of shelby tube samples | Wet Density ($g/cm^3$) | | Dry Density ($g/cm^3$) | | Volumetric water content ($cm^3/cm^3$) | |
|---|---|---|---|---|---|---|---|
| | | mean | standard deviation | mean | standard deviation | mean | standard deviation |
| 1 | 21 | 1.83 | 0.064 | 1.63 | 0.057 | 0.205 | 0.0087 |
| 2 | 17 | 1.57 | 0.034 | 1.43 | 0.033 | 0.136 | 0.0046 |
| 3 | 23 | 1.66 | 0.034 | 1.58 | 0.033 | 0.078 | 0.0039 |

essential to the success of any logging program where accurate quantitative results are desired. To obtain a good field calibration it is necessary to have physical property measurements made on a large number of core samples from different depths in the borehole using methods that insure that samples are representative of the formation *in situ*, but also cover a large range of expected conditions. The use of a coring and drilling method which minimizes the disturbance of the water contents of the formation rock and core in near surface boreholes at Yucca Mountain (Hammermeister and others, 1985) presented an opportunity to study and develop field calibration methods with high quality data. This drilling technique and the large number of core samples which will be taken should allow very accurate calibrations to be developed.

3.1.3.2.3 Borehole geophysical applications

Porosity and water content information are both very important parameters which are used to model infiltration. Core measurements are expensive and time-consuming but provide good quality point measurements. Borehole geophysics provide a convenient method for measuring these same values over a continuous region but may not be the same high quality as core measurements. When combined, these two techniques will provide a complimentary logging program.

3.1.3.2.3.1 Prototype studies

Prototype tests have been conducted with single detector neutron and gamma-gamma tools. These tests have shown that a reliable means of decentralization coupled with multi-detector tools is necessary to achieve high quality, precision logs. Multi-detector neutron and gamma-gamma tools are currently being evaluated. These tools, having both good decentralization and two detectors will allow high quality logs to be produced in the future. Two-detector tools enable the analyst to correct logs for borehole rugosity. Two prototype calibration holes will be continuously cored to provide the range of densities and water contents required to develop adequate calibration procedures. The boreholes will be located in soil and rock that have the range of densities, water content, and mineralogy expected at Yucca Mountain. The tool configuration (i.e., source-detector spacing) will be evaluated to determine the suitability for Yucca Mountain and the influence of density, mineralogy, borehole rugosity, casing type and borehole diameter in these two calibration boreholes.

3.1.3.2.3.2 Site characterization

When the proper procedure and tool design is determined, new calibration holes will be cored to provide calibrations

that will be used for site characterization. The geophysical logs will then be run in all available boreholes to characterize the near-surface conditions. Geostatistics will then be used to help determine where additional areal data is needed for each parameter to reach desired accuracy levels (see Section 3.1.3.5). Those boreholes specifically associated with the infiltration program will be run several times to characterize changes in properties during natural-infiltration and artificial-infiltration experiments.

If it is determined that bulk density is required for proper calibration of the small, hand-held neutron-moisture meter, then the borehole logging will be used to provide that data. Historical data can be reevaluated using the newest calibration equation if it is assumed that bulk density has not changed over the time of logging (4-5 years). This dataset will be used to calibrate models of infiltration as well as produce a large database that will be incorporated into the geostatistical analysis to characterize hydrologic properties in three dimensions.

### 3.1.3.3 Surface geophysical investigations

There are a variety of surface geophysical methods which may be used during the shallow unsaturated-zone investigations. These include: (1) ground penetrating radar, (2) shallow refraction seismic, (3) geotomography, and (4) electromagnetics and resistivity. They will be used to: (1) estimate the thickness of the unconsolidated surficial materials, (2) identify caliche zones, (3) measure natural and artificial wetting fronts, and (4) investigate fracture geometry.

#### 3.1.3.3.1 Description of geophysical methods

The following discussion is a brief summary of the methods to be evaluated. The techniques listed are not all inclusive but are expected to cover the range of available surface techniques.

##### 3.1.3.3.1.1 Ground penetrating radar

Ground penetrating radar (GPR) is a geophysical technique which may be used to delineate subsurface bodies which have different dielectric or resistive properties (Benson and others, 1982). It operates by using an antenna to send electromagnetic (radar) pulses into the earth and measuring the time it takes for these pulses to be reflected back to the antenna by subsurface targets. The practical maximum depth of investigation with any technique utilizing electromagnetic radiation is limited by the *skin depth*, which is defined as the depth at which the original radiation has been attenuated to 37 percent (1/e) of its original amplitude. The skin depth (hence the depth of investigation) increases with decreasing conductivity,

magnetic permeability and signal frequency. This implies that for a given material, the depth of investigation may be increased by using a lower frequency antenna. It should also be noted that as the frequency is lowered, resolution is also lowered. The radar frequency must therefore be chosen to fit each geologic situation. The frequency is changed by simply changing antennas on the equipment. GPR is of very limited use if the materials between the antenna and the target are highly conductive. Some examples of highly conductive earth materials are clays, and saturated soils. Conversely, GPR may be expected to work best in materials which have a high resistivity, or low conductivity, such as dry silica sands and gravels (the major constituents of unconsolidated surficial materials at Yucca Mountain which remain dry to the contact with bedrock [see Figure 3.2-5, p. 3.2-19]).

#### 3.1.3.3.1.2 Shallow refraction seismic

The refraction seismic method is used to detect subsurface velocity variations. It utilizes an impulsive energy source (sledgehammer, explosives, weight drop, etc.), a series of seismic detectors (geophones), and a device for recording the collected information (seismograph). The geophones (usually 12) are normally arranged in line with the source. The time that it takes for a seismic wave to travel from the source to each detector is plotted on a time-distance graph. This graph can be used to infer subsurface geologic information (Sjögren, 1984). The refraction seismic method will yield the most accurate results if the subsurface velocity layers are well defined, continuous, and their velocities increase with depth.

#### 3.1.3.3.1.3 Geotomography

Geotomography, when coupled with ponding experiments, can be used to map the flow paths of infiltrating water (Ramirez and Dailey, 1984). From these flow paths, fracture geometry (if present) may be inferred. In this method, a high-frequency (300 MHz) electromagnetic signal is transmitted between two or more coplanar boreholes. The position of the transmitter and receiver are arranged in various relative positions up and down the boreholes to obtain a large number of transmission paths through the rock or sediment. The transmitted signal, being influenced by the electrical conductivity and dielectric constant of the material between the transmitter and receiver, is attenuated to various degrees. To determine the distribution of signal attenuation, the region between the boreholes is divided into many cells and an attenuation rate is calculated for each cell from line integral equations for each transmission path. A map is then constructed of the distribution of attenuation between the boreholes. If the mapping of attenuation is performed before and after an infiltration

experiment into fractured rock in which water containing a saline tracer is used, the difference in the two images is a representation of the flow pathways. Geotomography will contribute some information on fracture distribution and fracture orientation.

3.1.3.3.1.4 Electromagnetics and resistivity

Resistivity and electromagnetic methods respond to variations in the resistivity of earth materials. The resistivity method involves measuring the potential generated between two electrodes by forcing a current between them. These values may then be converted into an apparent resistivity value which is a function of true earth resistivity (Telford and others, 1976). The electromagnetic method responds to the same physical properties in the earth. It, however, operates by inducing and measuring current flow in the earth with a pair of coils. The depth of investigation is limited by the skin depth (discussed in Section 3.1.3.3.1.1), as are all electromagnetic methods. The electromagnetic method is most useful as a tool to rapidly measure lateral variations in earth resistivity. The resistivity method may also be used in this capacity, but it is also effective as a tool to measure vertical variations in resistivity.

As the prototype development work progresses, it is possible that other potential geophysical applications will be identified. At that time they will be evaluated and used as needed.

3.1.3.3.2 Application of geophysical methods

The following discussion is directed at the application of surface-geophysical methods for specific purposes. Again, this list is not all-inclusive, as other applications may be developed as experience and technology develop.

3.1.3.3.2.1 Thickness of surficial materials

The thickness of unconsolidated surficial materials is an important factor in determining net infiltration as discussed in Section 2.1.3. The purpose of this investigation is to determine the thickness of the unconsolidated surficial materials or, the maximum detectable depth to bedrock. If a zone of evapotranspiration can be determined (see Section 2.1.3), the knowledge of the distribution of unconsolidated materials below that depth can be used to help identify regions of differing mechanisms for net infiltration. Boreholes are the best indicator of depth to bedrock, but these point measurements need to be supplemented with other techniques to obtain detailed areal coverage.

3.1.3.3.2.1.1 Prototype studies

During the prototype studies, several methods will be evaluated to investigate their relative applications and suitability for measuring the depth to bedrock on and around Yucca Mountain. These methods are: (1) shallow seismic refraction, (2) ground penetrating radar, and (3) indirect processes such as slope estimation techniques.

Preliminary seismic work has been carried out by both the Geologic Division and the Nuclear Hydrology Program of the U.S. Geological Survey. The Geologic Division has conducted deep seismic refraction surveys in the vicinity of Yucca Mountain (Pankratz, 1982) to study lithology, stratigraphy, and faulting. The Nuclear Hydrology Program has also conducted preliminary prototype shallow refraction surveys to evaluate the potential for determining the depth of surficial materials over bedrock (Kneiblher, 1985). Both groups have found that seismic velocities in alluvium are typically less than 1,200 m/sec, while velocities in welded bedrock range from 1,500 to 3,000 m/sec. In most cases the velocity contrast between the bedrock and the unconsolidated surficial materials is large enough to permit the contact between these units to be located. The seismic refraction technique has been used successfully at several locations on Yucca Mountain as a means of measuring the depth to bedrock. Seismic surveys were done in a narrow canyon (a relatively difficult location) with good results (Figure 3.1-5). The depths calculated by seismic refraction were found to correlate well with borehole depths. Further work, where borehole data are available, is currently being conducted.

The geologic nature of the materials on Yucca Mountain limit the use of seismic refraction to depths no greater than about 30 meters or shallower than about 2 meters. The maximum depth of investigation is caused by the fact that the surficial materials on Yucca Mountain rapidly filter out high frequency components from the seismic wave and make it impossible to determine depth to bedrock with any precision. The minimum depth of investigation exists because materials which are essentially homogeneous in bulk, become very heterogeneous when they are examined in detail by the seismic method. This means that results will be complicated by large rocks and differences in the consolidation of the near surface materials. It will also be difficult to obtain accurate depths to bedrock using seismic refraction at locations where the surficial materials contain high velocity zones (such as well-formed caliche layers, which are soil layers

cemented by calcium carbonate, and developed in locations with high evaporation), discontinuous layering, or at locations where the bedrock is highly attenuating (typically from fracturing).

Ground penetrating radar (GPR) is also being investigated for its suitability for determining the depth to bedrock. Tests conducted on surface soil samples from Yucca Mountain indicate that GPR should have very good penetration in the surficial materials. The arid environment, coarse-sandy nature of the soils and low clay contents are all favorable elements for a successful application of GPR. If GPR methods prove

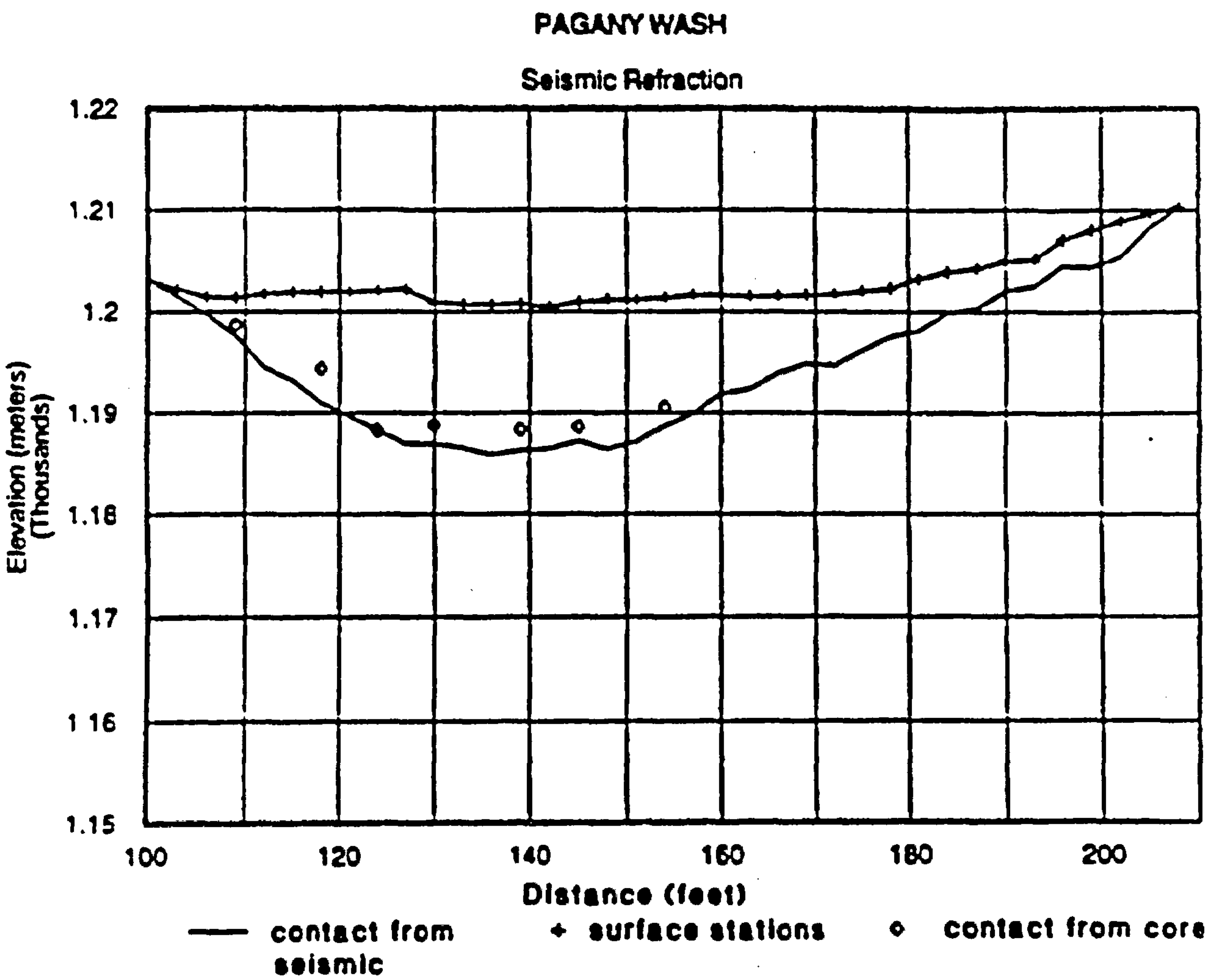


Figure 3.1-5. Diagram showing cross-section of Pagany Wash showing surface locations of seismic survey, depth to bedrock determined from borehole core samples, and estimates of depth to bedrock from seismic refration survey.

suitable, it is expected to be most useful for detailed shallow-depth studies, and in narrow canyons, where space constraints make seismic refraction difficult. GPR techniques should also be faster in the field, and take less time to interpret than the refraction-seismic method. One complicating factor for GPR is its sensitivity to radio frequencies. There is a tremendous amount of radio frequency interference from Air Force and Nevada Test Site activities which may limit the ability to use GPR.

Indirect methods using geologic information and other observations (such as slope measurements of exposed bedrock) will also be tested as a means to estimate depth to bedrock at locations where seismic refraction and GPR are unsuitable. These techniques will also provide some confidence in the geophysical techniques, as it is independent of the characteristics of the unconsolidated surficial materials.

3.1.3.3.2.1.2 Site characterization

Upon completion of the prototype studies to determine the thickness of surficial materials, site characterization work will begin. The three methods described earlier will be used as needed. Because these methods are each affected by different physical properties, it is expected that they may complement each other well. Maps will be produced to show the thickness of unconsolidated surficial materials for the study area. These maps will be combined with other information and refined as necessary by specific site measurements (such as borehole depth to bedrock).

3.1.3.3.2.2 Identification of caliche zones

An important component of the unconsolidated surficial materials is the presence of caliche layers. These layers are relatively impermeable (unless fractured) and may be of major importance in restricting net infiltration. These layers may be continuous over large areas, which could cause perched-water conditions to occur just below the surface. Surface-geophysical surveys may be useful in identifying the zones of caliche and also determining the continuity from point to point.

3.1.3.3.2.2.1 Prototype studies

Two methods that may be suited for identifying caliche zones are refraction seismic and ground penetrating radar. Preliminary work indicates that a well developed caliche layer in this area may be expected to have a seismic velocity of about 1200 m/sec. It may therefore be possible to identify these zones with seismic

refraction if the overlying soils are unconsolidated and have a lower velocity (<1200 m/sec) while bedrock is denser with a higher velocity (>1200 m/sec).

GPR may also be useful in identifying areas where caliche exists, particularly if discontinuous layers exist yielding sharp contrasts in reflection time. If perched water occurs, surface resistivity and electromagnetics may be useful.

3.1.3.3.2.2.2 Site characterization

Once the methods have been evaluated then technical procedures will be written and site-characterization activities will begin. Areal distribution of caliche zones will be mapped. These zones will be analyzed as part of the natural- and artificial-infiltration studies.

3.1.3.3.2.3 Determination of wetting-front location

Distinct wetting fronts may exist for short periods of time following major precipitation events. Surface geophysical techniques may be useful in monitoring this front in three dimensions (borehole measurements are limited to one-dimensional point measurements). It may be possible to determine the zone of evapotranspiration (Section 2.1.3) by monitoring the wetting-front location and combining that information with surface-evapotranspiration measurements.

3.1.3.3.2.3.1 Prototype studies

Two methods which have the potential for finding the lateral and vertical extent of a wetting front (naturally or artificially induced) are the resistivity and the electromagnetic methods (Telford and others, 1976). Both of these methods respond to variations in the resistivity of earth materials, which vary with time due to changes in soil moisture content. There is a possibility of automating the system, which would improve the likelihood of examining precipitation events of the magnitude necessary to penetrate great depth, since they are infrequent and could easily be missed using manual systems. The time required for a manual survey, although unknown at this time, may be prohibitively long.

3.1.3.3.2.3.2 Site characterization

If either, or both, of these methods are found to be useful for determining the location of wetting fronts, they will be used during site-characterization studies after technical procedures are written. The presence or

absence of restrictive layers will also be determined from this technique if good resolution is obtained.

3.1.3.3.2.4 Fracture geometry and hydraulic properties

Fractures may be important pathways for water flow through the tuffs (including surficial units) at Yucca Mountain (Montazer and Wilson, 1984). Unfortunately, geophysical methods, which are useful in characterizing the physical and hydrologic properties of the rock matrix, are not generally useful for characterizing rock-fracture properties. Therefore, there is a need to develop and test methods to characterize the geometry of fracture systems. In addition, it would be advantageous if these same methods could be used to characterize the hydraulic properties of the fracture system. Recent advances in high-resolution geotomography (Dailey and Ramirez, 1984), when coupled with infiltration experiments, can be used to provide information on the hydraulic and transport properties of fracture systems and possibly on fracture geometry including variation of fracture apertures.

Geotomography has the potential of producing a cross-sectional image of the subsurface distribution of the electrical conductivity and the dielectric constant between boreholes (Ramirez and Dailey, 1984). Electrical conductivity is related to water salinity and rock mineralogy, and the dielectric constant is related to water content. Therefore, if a saline tracer (such as lithium bromide) is added to water infiltrating into rock, it is theoretically possible to monitor both the changes in water content and the movement of the saline tracer. The imaging procedure involves transmitting a high-frequency electromagnetic signal between two or more boreholes. The position of the transmitter and receiver are varied within the boreholes to yield an effective, two-dimensional image of the distribution of the dielectric constant and electrical conductivity values. Images are reconstructed from measurements of amplitude and phase change at the receiver compared to differences at the transmitter.

It is still an open question how to relate the preferred flow paths of a saline tracer as determined by geotomography to fracture geometry. Tracer flow paths in saturated fractures have been shown to be related to variability of fracture apertures (Tsang and Tsang, 1989). The sensitivity of flow paths to fracture apertures in an unsaturated system will be even more significant. Supposing this effect on fracture density and orientation would make this a highly non-unique inverse problem in characterization of fracture geometry. Nevertheless the measurements proposed will give significant information on the overall hydraulic and transport properties of the fracture system at the site.

Prototype tests will be conducted in conjunction with prototype ponding tests to evaluate the potential of using geotomography to characterize the properties of the near-surface fractured rock. If these preliminary tests are successful, they will be used for site characterization.

3.1.3.3.2.4.1 Prototype studies

Prototype geotomography-ponding tests will be done in conjunction with prototype ponding tests (Section 3.3). Ponding tests involve applying a constant water pressure to the soil surface and then measuring infiltration rate, water content and water potential in the profile with time. Redistribution and drainage will be monitored after the water input is discontinued. For the purpose of prototyping geotomography, at least 3 boreholes will be drilled to a depth of 9 meters in the infiltration plot. Fracture density and orientation from core samples from these holes will be characterized. Mapping of attenuation will be done before, during, and after infiltration experiments, and the results compared to fracture characterization determined through core analysis and infiltration plot excavation.

3.1.3.3.2.4.2 Site characterization

If prototype tests indicate that geotomography can be used successfully to characterize the fracture geometry and hydrologic properties of fracture systems beneath artificial-infiltration plots, technical procedures will be written to apply these methods in site characterization.

3.1.3.3.2.5 Other possible geophysical applications

As prototype investigations proceed, other possible geophysical applications may become evident. It may, for instance, be possible to identify some fracture zones with GPR. If additional applications are identified, they will be evaluated and used as necessary.

3.1.3.4 Remote sensing

Remote sensing of reflected and emitted electromagnetic radiation offers a rapid method to characterize surficial materials. If the physical characteristics of the surface show a correlation with hydrologic characteristics and responses, then remote sensing can be used to obtain these parameters over wide areas (Kolm, 1985). Remote-sensing techniques developed within this activity will be used in conjunction with Studies 8.3.1.5.2.1 (Characterization of the Quaternary regional hydrology), 8.3.1.17.4.7 (Subsurface geometry and concealed extensions of Quaternary faults at Yucca Mountain), and 8.3.1.2.1.3 (Characterization of the regional ground-

water flow system). Data collection from these studies will provide support for estimating values of potential infiltration (this activity), potential discharge (Activity 8.3.1.5.2.1.3), and for use in regional fracture-zone hydrology (Activity 8.3.1.17.4.7.7). These data will also be used to support regional saturated-zone and paleohydrologic modeling (indirectly through Study 8.3.1.2.1.3).

When an electromagnetic wave interacts with matter, five phenomenon occur: reflection, transmission, absorption, scattering and emission. The degree to which the electromagnetic energy is split among these components is a function of the frequency of the wave and the molecular and atomic structure of the object upon which the wave is incident or emitted. Because of the unique physical makeup of many objects, the interaction of matter and energy often results in a unique spectral response for the object or class of objects. For example, the sharp variation of chlorophyll reflectivity near the wavelength of 0.75 um is extensively used in vegetation mapping. In the band between 0.84 and 0.92 um, electromagnetic energy is strongly absorbed, which is associated with $Fe^{3+}$, and is an indication of the presence of iron oxides and hydrous iron oxides.

Remote-sensing methods applied to Yucca Mountain will be used primarily to help define infiltration-runoff map units and the changes that may occur within these units as a result of precipitation or other meteorological changes. Infiltration-runoff map units that have been identified by sampling, testing and mapping activities will be compared with units defined by common spectral characteristics as outlined in Section 3.1.3.1. Spectral characteristics which correlate well with infiltration-runoff map units in the representative canyon-ridge system will be used to help define the boundaries of these units over all of Yucca Mountain.

In addition, thermal remote-sensing data will be collected before and after precipitation events and at different times of day when possible. These data will be analyzed to describe changes which occur in hydrologic conditions of the surficial materials as a function of precipitation and other meteorological parameters such as temperature, relative humidity, wind speed and solar radiation. These meteorological data will be collected at weather stations spaced over Yucca Mountain and located on representative surficial materials. Plans for the collection of meteorological data are described in Study 8.3.1.2.1.1 (Characterization of the meteorology for regional hydrology) and in Section 3.2.3.4.2.3.4.

### 3.1.3.4.1 Prototype studies

Prototype tests will be done on a representative canyon-ridge system of Yucca Mountain to determine the feasibility of calibrating remote-sensing imagery data with hydrologic properties and conditions of soils and surficial rocks (infiltration-runoff map units). Calibration methods will also be evaluated. The available remote-sensing data that will be analyzed will include Landsat Thematic Mapper (TM) imagery with

three infrared (IR) bands, one thermal band, and three visible bands; Landsat Multi-Spectral Scanner (MSS) imagery with two IR bands and two visible bands; Skylab photography, including color, color IR, and black and white photos; Side Looking Airborne Radar (SLAR) imagery; and Low Altitude Thermal Scanner (LATS) imagery. Climatic data include cloud type, amount, and height; horizontal visibility; wind direction and speed; dew-point, wet-bulb and dry-bulb temperature; relative humidity; and atmospheric pressures as a function of altitude.

Landsat TM and MSS data will be analyzed by a number of established computer classification methods to develop units with common spectral characteristics. These computer classification methods include principal component analysis, unsupervised/supervised techniques, false-color infrared supervised stretch techniques, and band 7 to band 5 ratio cut-off stretch procedures. These methods are described by Kolm and Case (1984), Sabins (1978), and Abrams and others (1984). Permutations and combinations of the above methods will also be used to analyze TM data which contain seven bands and have better resolution. These various classification methods will be evaluated for both TM and MSS data by comparing and correlating computer classification results with infiltration-runoff map units measured for the representative canyon-ridge system.

Aerial photographs including Skylab, high-altitude photography (HAP), and low-altitude photography (LAP) data will be analyzed manually by established procedures (Sabins, 1978) to determine its usefulness in defining infiltration-runoff map units as described previously for TM and MSS data analysis. LATS and SLAR data will be analyzed by digital-enhancement methods to specifically characterize the temporal changes in the distribution of surficial-material water contents. If possible, LATS and SLAR flights will be flown before and after precipitation events to study the effect of different types of precipitation events and the seasonal variation in other meteorological parameters on the distribution and changes in water content. Field measurements of water content before and after precipitation events will be used to evaluate the usefulness of the remote-sensing method to monitor water-content changes. If either of these methods prove useful, the water data generated should be helpful in extrapolating *in situ* point measurements of infiltration, runoff, and evapotranspiration over larger areas of Yucca Mountain.

### 3.1.3.4.2 Site characterization

If the spectral characteristics of TM, MSS, Skylab, HAP and LAP remote-sensing imagery correlate well (which may depend on their spatial resolution) with measured infiltration-runoff units and/or hydrologic conditions in the prototype study area, technical procedures will be written to use remote-sensing methods in site characterization. Remote-sensing methods will be incorporated with the mapping methods described in Section

3.1.3.1 and infiltrometry methods described in Section 3.3.3.1.1 to map all of Yucca Mountain. Acceptable levels of correlation will be determined after prototype tests are completed.

If LATS and/or SLAR methods prove successful in monitoring water-content changes in the surficial materials of the prototype test area, the methods will also be used to monitor water-content changes over all of Yucca Mountain after specific precipitation events.

3.1.3.5 Geostatistical analysis of the spatial variability of surficial materials

In trying to characterize hydrologic-surficial units at Yucca Mountain, it is impossible to adequately sample and test the entire region to obtain a deterministic evaluation of surficial physical and hydrologic parameters. In addition, it is not possible to estimate, *a priori*, the number and location of tests. Therefore, geostatistical methods will be used to estimate parameters from "available" data. Autocorrelation functions, semivariograms, and cross-semivariograms will be used to develop appropriate models for spatial structure for each hydrologic parameter. Kriging, and co-kriging (Journel and Huijbregts, 1978) will be used to estimate hydrologic properties between measuring points and to provide a measure of the uncertainty of the estimates. Estimates obtained from geostatistical techniques will be combined with all available laboratory and field data to delineate hydrologic-surficial units at Yucca Mountain and to obtain input needed for larger unsaturated-zone models.

3.1.3.6 Methods summary

The parameters to be determined by the tests described above are summarized in Table 3.1-2. Also listed are the selected and alternate methods for determining the parameters and the current estimate of the parameter-value range. The alternate methods will be used if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, only the most common methods are included in the table. The selected methods in Table 3.1-2 were chosen primarily on the basis of accuracy, precision, duration of methods, expected range, and lack of interference with other tests and analyses.

The USGS investigators have selected methods which they believe are suitable to provide accurate data within the expected range of the site parameter. Models and analytical techniques have been or will be developed to be consistent with test results. In addition, it is not possible to estimate, *a priori*, the numbers and locations of tests.

3.1.4 Technical procedures

The USGS quality-assurance program plan for the YMP (USGS, 1986) requires documentation of technical procedures for all technical activities that require quality assurance.

Table 3.1-2. Summary of tests and methods for characterization of hydrologic properties of surficial materials activity (SCP 8.3.1.2.2.1.1)

[Dashes (--) indicate information is not available or not applicable.]

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Sampling, testing, and mapping** | | |
| Determine areal distribution of surficial materials and hydrologic properties through geologic mapping (selected) | Infiltration-runoff map units | -- |
| Map bedrock outcrops by field mapping (selected) | Bedrock outcrop | -- |
| Map bedrock outcrops from aerial photography (selected) | " | -- |
| Map bedrock outcrops by estimation from geologic maps (selected) | " | -- |
| Measure density by bead-cone method (selected) | Bulk density | 0.5 to 2 g/cm³ |
| Measure density by sand-cone method (alternate) | " | " |
| Measure density by laboratory analysis of lithologic samples (alternate) | " | 1 to 2 g/cm³ |
| Measure density by surface nuclear-density gauge method (alternate) | " | 1 to 2.6 g/cm³ |
| Measure porosity by displacement method (selected) | Porosity | 0.05 to 0.60 cm³/cm³ |
| Calculate porosity from density values (selected) | " | " |
| Measure texture by laboratory determination of grain-size distribution of field samples (selected) | Texture | Most textural groups |

Table 3.1-2. Summary of tests and methods for characterization of hydrologic properties of surficial materials activity (SCP 8.3.1.2.2.1)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Sampling, testing, and mapping--Continued** | | |
| Measure texture by "feel" method (selected) | Texture | Most textural classes |
| Measure soil and alluvium thickness by excavating lithologic samples (selected) | Soil and alluvium thickness | 0 to 10 m |
| Measure soil and alluvium thickness by continuous coring/drilling (selected) | " | " |
| Measure gravimetric-water content by weight loss from oven drying (selected) | Gravimetric-water content | 0 to 100% saturation |
| Measure gravimetric-water content using "speedy" moisture meter (selected) | " | " |
| Measure gravimetric-water content by weight loss using microwave oven drying (selected) | " | " |
| Measure water potential of field samples by Richards thermocouple psychrometry (selected) | Water potential | 100 to 10,000 J/kg |
| Measure water potential of field samples by Peltier thermocouple psychrometer (selected) | " | " |
| Measure water potential of field samples by filter paper method (selected) | " | 100 to 10,000 J/kg |
| Measure water potential of field samples by osmotic tensiometry (selected) | " | 0 to 1,500 J/kg |

Table 3.1-2. Summary of tests and methods for characterization of hydrologic properties of surficial materials activity (SCP 8.3.1.2.2.1.1)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Borehole geophysical investigations** | | |
| Measure density profiles by gamma-gamma logging (selected) | Bulk density | 1 to 2.5 g/cm$^3$ |
| Measure density profiles by laboratory analysis of continuous core samples (selected) | " | " |
| Measure porosity by displacement method (selected) | Porosity | 0.05 to 0.60 cm$^3$/cm$^3$ |
| Calculate porosity from density values (selected) | " | " |
| Measure water-content profiles by neutron porosity (selected) | Water-content profiles | 0 to 100% saturation |
| **Surface geophysical investigations** | | |
| Determine soil and alluvium thickness using shallow surface-seismic refraction techniques (selected) | Soil and alluvium thickness | 0 to 10 m |
| Determine soil and alluvium thickness using ground-penetrating radar (selected) | " | " |
| Determine soil and alluvium thickness using electromagnetic and resistivity techniques (selected) | " | " |
| Determine fracture density using geotomography in conjunction with artificial-infiltration tests (selected) | Fracture density | -- |

Table 3.1-2. Summary of tests and methods for characterization of hydrologic properties of surficial materials activity (SCP 8.3.1.2.2.1)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| | *Surface geophysical investigations--Continued* | |
| Determine fracture density by laboratory analysis of continuous core samples (selected) | Fracture density | -- |
| Determine fracture orientation using geotomography in conjunction with artificial-infiltration tests (selected) | Fracture orientation | -- |
| Determine fracture orientation by laboratory analysis of continuous core samples (selected) | " | -- |
| Determine flow pathways in conjunction with artificial-infiltration tests (selected) | Flow pathways | -- |
| | *Remote sensing* | |
| Computer-aided analysis of LANDSAT thematic mapper (TM) spectral data (selected) | Correlation of surficial-materials properties with spectral responses | -- |
| Manual analysis of high and low-altitude aerial photography (selected) | " | -- |
| Analysis of low-altitude thermal scanner (LATS) data (selected) | Surficial-materials water content | -- |
| Analysis of side-looking airborne radar (SLAR) data (selected) | " | -- |
| Determine areal distribution of surficial materials and hydrologic properties through spectral response from LANDSAT TM (selected) | Infiltration-runoff map units | -- |

Table 3.1-2. Summary of tests and methods for characterization of hydrologic properties of surficial materials activity (SCP 8.3.1.2.2.1)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Geostatistical analysis** | | |
| Geostatistical analysis to determine spatial variability of hydrologic properties of surficial materials (selected) | Spatial variability of hydrologic properties of surficial materials | -- |
| Classical statistics to determine spatial variability of hydrologic properties of surficial materials (selected) | " | -- |

Table 3.1-3 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a USGS procedure number and an effective date. Procedures that are not identified with an effective date will be completed and available 30 days (for standard procedures) or 60 days (for non-standard procedures) before the associated testing is started; these procedures are also identified with a "TBD" (To Be Determined) technical procedure number. Some of the listed technical procedures are primarily outside the objectives of the subject activity, but are included for general information and ease of cross referencing. Approved technical procedures not listed may be used during the activity, should that be appropriate, and listed procedures may be revised or replaced with other procedures, as needed.

Applicable quality-assurance procedures are presented in Appendix 7.1.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, and calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

Table 3.1-3. Technical procedures for characterization of hydrologic properties of surficial materials (SCP 8.3.1.2.2.1.1)
[Dashes (--) indicate information is not available and to be determined.]

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Sampling, testing, and mapping** |
| HP-12 | Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS |
| HP-32 | Method for monitoring moisture content of drill-bit cuttings from the unsaturated zone |
| HP-136 | Methods for handling and storage of drill cuttings and core from unsaturated-zone boreholes at the unsaturated-zone testing laboratory (Test Cell C) |
| | **Borehole nuclear-geophysical logging** |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |
| | **Surface geophysical investigations** |
| TBD | Method for determining soil and alluvium thickness using shallow surface-seismic techniques |
| TBD | Method for determining soil and alluvium thickness using ground penetrating radar |
| TBD | Methods for determining soil and alluvium thickness using electromagnetics and resistivity techniques |
| TBD | Method for determining fracture characteristics using geotomography |

Table 3.1-3. Technical procedures for characterization of hydrologic properties of surficial materials (SCP 8.3.1.2.2.1.1)--Continued

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | Geostatistical analysis of the spatial variability of surficial materials--Continued |
| TBD | Characterization of spatial variability of surficial hydrologic properties |

## 3.2 Evaluation of natural infiltration

### 3.2.1 Objectives

The objective of this activity is to characterize present-day infiltration processes and quantify net-infiltration rates in the surficial materials of Yucca Mountain.

### 3.2.2 Rationale for activity selection

This activity is designed to characterize natural-infiltration rates, water content, water potential, and evapotranspiration of the surficial materials of Yucca Mountain under present-day climatic conditions. This information is required to model water flow through the thick-unsaturated zone beneath Yucca Mountain.

### 3.2.3 General approach and summary of tests and analyses

The characterization of present-day infiltration processes and quantifications of net-infiltration rates in surficial materials at Yucca Mountain will be accomplished by five major tests and analyses:

1. Neutron-access borehole studies will be used to monitor natural infiltration by periodically measuring water contents at 100 locations to depths up to 30 m (98 ft).

2. Artificial-infiltration control plot studies will monitor natural infiltration beneath rainfall-simulation plots located in each of the geohydrologic-surficial units.

3. Tritium-profiling studies on core obtained from neutron-access boreholes will help determine flow pathways and net infiltration. Net infiltration, as determined from these studies, will be a collection of spatial point values, averaged in time over the last 30 to 40 years.

4. Water-budget studies will provide calculated net infiltration by analyzing precipitation, runoff, evapotranspiration and storage measurements.

5. Geostatistical analysis of natural-infiltration data will be used to determine spatial distribution and locate new sampling sites.

Each of these will be discussed in turn.

Figure 3.2-1 summarizes the organization of the natural-infiltration activity. A descriptive heading for each test appears in the boxes of the second row. Below each test is the individual method that will be utilized. Figure 3.2-2 summarizes the objectives of the activity, design- and performance-parameter categories which are addressed by the activity, and the site parameters measured. These appear in the boxes in the top left

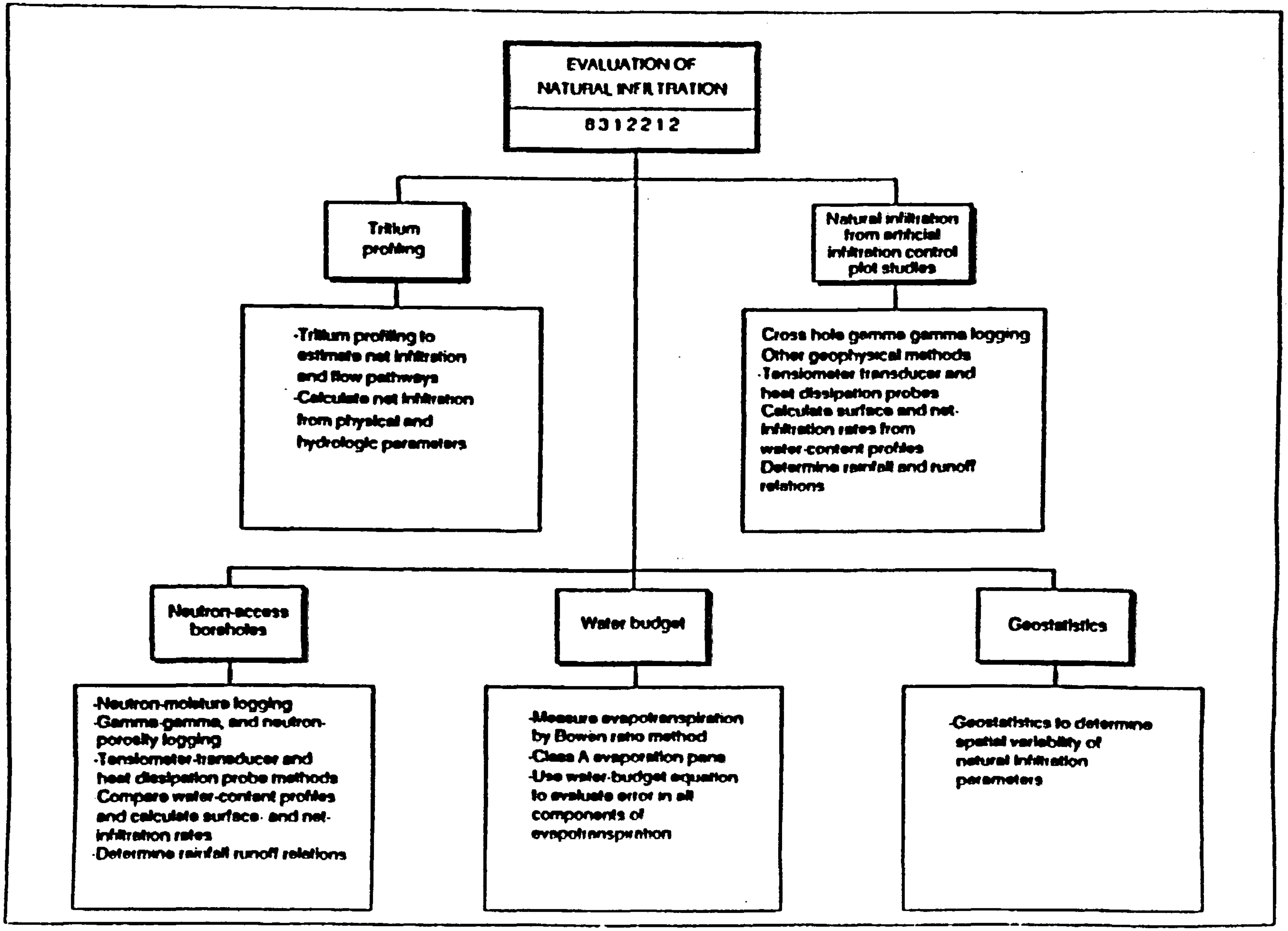


Figure 3.2-1. Logic diagram for natural inf[illegible]ation showing tests, analyses and methods.

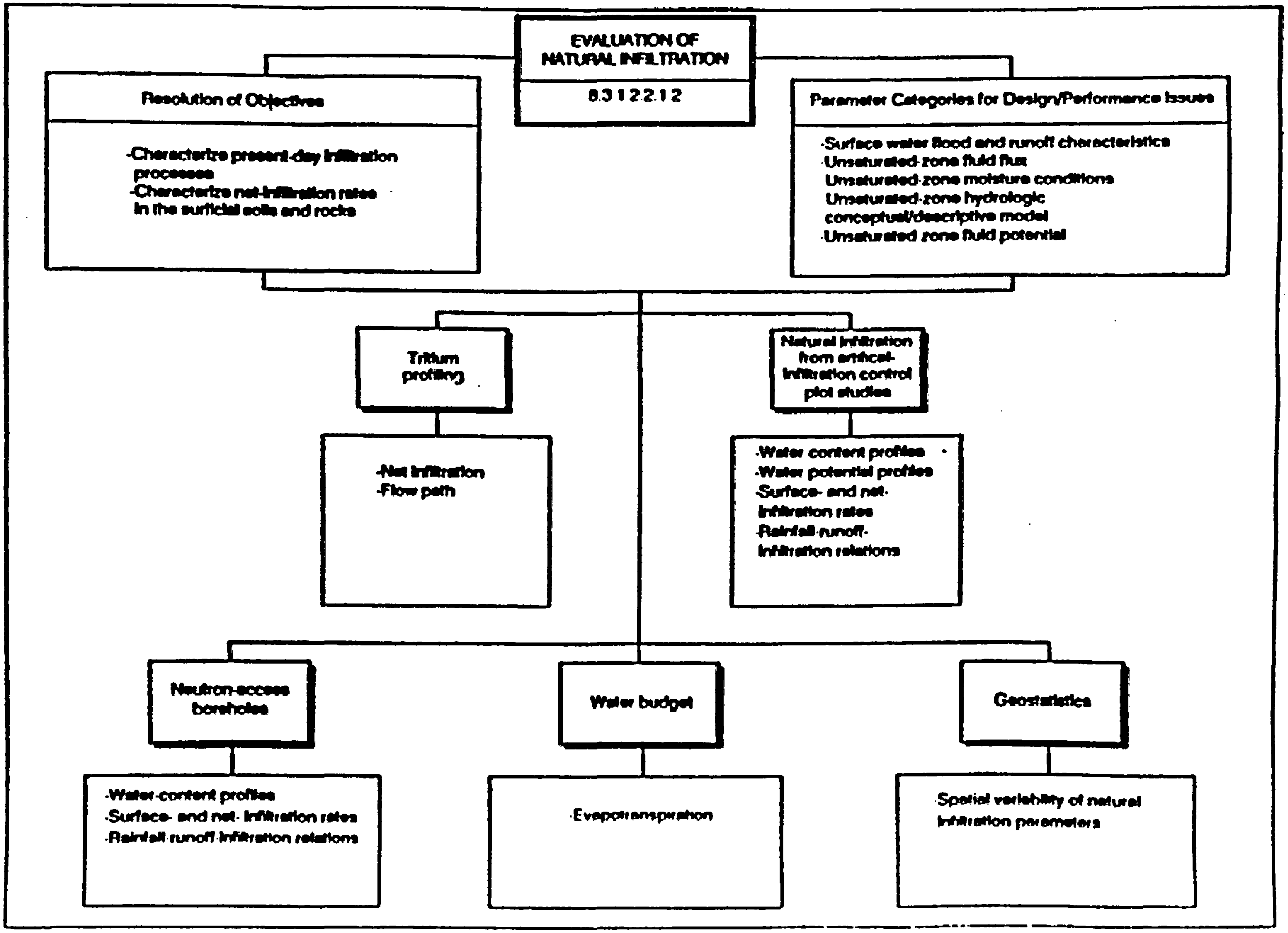


Figure 3.2-2. Logic diagram of natural infiltration showing tests, analyses, and site parameters

side, top right side, and below the test boxes, respectively, in Figure 3.2-2.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the site parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The tests utilized in the natural-infiltration activity will provide information that is representative of the repository area. The spatial variabilities of existing conditions within the repository area, and the correlations to present and potential future repository conditions are represented by this activity.

3.2.3.1 Neutron-access boreholes

Neutron-access borehole studies will be used to monitor natural infiltration in 74 currently located neutron-access holes and, as planned, an additional 24 holes which will be located to better represent topographic surfaces in all geohydrologic-surficial units. It is not known at this time if the additional 24 holes will be adequate. Further analysis will be required to determine if more holes are needed to adequately characterize natural infiltration. This will be accomplished by installing additional neutron-access boreholes and further developing a detailed monitoring program using neutron-moisture meters.

3.2.3.1.1 Monitoring criteria and hypotheses

Net infiltration is defined as the amount of water that has infiltrated deep enough so that it does not return to the atmosphere by evapotranspiration or by some other flow mechanism. This water may or may not reach the saturated zone as recharge. In this study, it is arbitrarily assumed that water which infiltrates nine meters (30 feet) below the land surface is net infiltration. Unfortunately, there are no widely applicable rules which state at what depth percolation becomes net infiltration. Furthermore, there is a scarcity of data concerning net infiltration in any type of geohydrologic unit in desert climates. The depth at which infiltration becomes net infiltration depends upon the surficial materials, including bedrock properties, vegetation cover and climate. This initial assumption, or hypothesis, will be revised as net-infiltration data are collected. Therefore, the neutron-access boreholes are intended to be drilled deep enough to monitor net infiltration.

As discussed earlier (Section 2.1.3), the zone of evapotranspiration is of critical importance in characterizing net infiltration. The neutron-monitoring program will be used as much as possible to help define the lower limit of that zone.

The boundary between the zone of evapotranspiration and percolation is a theoretical zero flux plane. This boundary can be located using a method, developed by Richards and others (1956), which partitions water loss from a soil layer into evapotranspiration and percolation losses (Dreiss and Anderson, 1985). In situations where water flow is vertical, the zero flux plane is horizontal, and is defined by a reversal in the direction of unsaturated hydraulic gradient. Above the zero flux plane, the hydrologic gradient is directed vertically upward, and all decreases in water content are assumed to result from evapotranspiration. Below the zero flux plane, the hydrologic gradient is vertically downward, and all decreases in water content are assumed to reflect net infiltration. Under these conditions, the amount of water contributing to net infiltration is recorded as a decrease in water content below the zero flux plane.

The location of the zero flux plane is expected to be spatially and temporally variable. There are several methods available to quantify the location: (1) mass balance between water content and measured evapotranspiration on the same time scale, (2) water-content profiles converted to water potential by analytical techniques, and (3) surface geophysical techniques, as described in Section 3.1.3.3.

3.2.3.1.2 Technical criteria and prototype studies

Nuclear logging, especially neutron-moisture logging, is very sensitive to borehole conditions (Keys and MacCary, 1972). Therefore, in order to maximize the potential for successfully using nuclear logging to monitor infiltration on Yucca Mountain, the USGS has developed strict criteria for selecting the drilling, coring and casing methods for neutron-access boreholes. Criteria for the selection are:

1. The method should minimize the disturbance of the formation by drilling fluids.

2. The method should be capable of drilling in a variety of geologic and topographic settings.

3. The method should permit the insertion of the casing into unconsolidated materials and bedrock, and it should minimize the void space between the casing and the formation.

4. The method should be able to provide lithologic-core samples with hydrologic properties that are representative of the formation. These samples are needed to conduct field calibrations for the nuclear-logging tools.

A discussion of testing of various drilling, coring, and casing methods follows in Section 3.2.3.1.2.1. A further discussion of infiltration monitoring in existing boreholes is given in Section 3.2.3.1.2.2.

3.2.3.1.2.1 Drilling, coring and casing tests

Tests have been conducted to determine the best method for installing neutron-access boreholes. These tests examined the following methods: (1) hollow-stem auger, (2) the ODEX system, (3) drive-coring, and (4) rotary air coring.

The hollow-stem auger method proved to be unsuccessful in unconsolidated materials. After the auger reached the intended depth, a 150-mm (6-in) O.D. diameter casing was to be placed inside the hollow stem. Then the auger's rotation would be reversed, causing the formation to cave in on the casing. Unfortunately, the bouldery nature of the Yucca Mountain deposits prevented the hollow-stem auger from penetrating more than 2 m (7 ft) into the surficial materials.

The ODEX 115 drilling and casing system (Hammermeister and others, 1985) was originally designed in Sweden to drill through glacial till to bedrock. This method uses a downhole-percussion hammer to drill and ream as it advances the casing. A pilot bit, in conjunction with an eccentric reamer, drills a hole slightly larger than the outside diameter of the casing. The percussion hammer impacts on the casing through a shoe which is attached to the bottom joint of the casing. Thus, the casing is advanced downward as the hole is deepened. Drill cuttings are returned to the surface through the inside of the casing, thereby minimizing the disturbance of the borehole walls with drilling fluids. With air as the drilling fluid, this method demonstrated that it could meet all of the criteria required for drilling neutron-access boreholes. Formation water content was minimally disturbed and some of the drill cuttings filled the small annular spaces between the casing and formation, minimizing the void space.

To obtain core samples from unconsolidated deposits, a drive-core method was tested. This was accomplished by attaching the drive-core barrel to the ODEX hammer. The powerful hammer successfully drove the drive-core sampler into the surficial materials.

Prototype rotary air-coring tests proved successful in obtaining minimally disturbed geologic core from nonwelded to welded tuffs. The USGS had previous success using rotary air-coring techniques on nonwelded tuff in New Mexico (Teasdale and Pemberton, 1984). A diamond surface-set bit was used in densely welded tuff and a carbide stagger-tooth bit was used in nonwelded tuff. A test on boulders indicated that rotary air-coring did not measurably disturb the water content of the core from *in situ* conditions. These drilling and coring methods and the effect they have

on the water content of cuttings and core from Yucca Mountain are described by Hammermeister and others (1985).

3.2.3.1.2.2 Logging tests

A review of the nuclear-logging literature indicated that it would be difficult to use neutron-moisture logging successfully in the 130-mm (5-in) inside diameter casing used with the ODEX 115 Drilling System. Neutron-moisture logging is commonly used in 50-mm (2-in) inside diameter casing which is slightly larger than the logging tool diameter (Wilson, 1982). Neutron-porosity logging tools, which are less sensitive to borehole conditions, would probably perform better in the relatively large-diameter ODEX casing (Keys and MacCary, 1972).

A preliminary calibration of the neutron-moisture meter has been established using core and cuttings from various boreholes. Two calibration equations were evaluated, one linear and one quadratic, using least-squares analysis (Figure 3.2-3). Although the $R^2$ values are similar ($R^2$=0.83 and 0.86 respectively), the quadratic equation appears to be a much better representation of the data. At low counts, the linear equation yields negative water contents, which eventually led to the development of the quadratic equation. To provide data in the whole range of expected water contents, it was necessary to estimate densities for about 30% of the samples. It was also necessary to use moisture-meter data collected as much as 3 months after the core and cutting samples were collected. This occurred, however, only in the welded units which, since then, have showed no appreciable water content changes.

Neutron-moisture meters are very reliable, easy to use, and relatively safe, compared to neutron-porosity tools, because they use a smaller radioactive source. These meters have been used in the neutron-access boreholes to monitor natural infiltration since July, 1984.

3.2.3.1.3 Site characterization

Drilling of the neutron-access boreholes began in June 1984. By February, 1986, 74 holes had been drilled. Twenty-four more holes will be drilled at a later date. Monitoring natural infiltration in these holes by neutron-moisture logging began in July, 1984. The following sections describe borehole locations and depths, the logging of these holes, and the procedures used to analyze the resulting data. Other neutron holes may be made available for this study (Fortymile Wash recharge activity, 8.3.1.2.1.3.3).

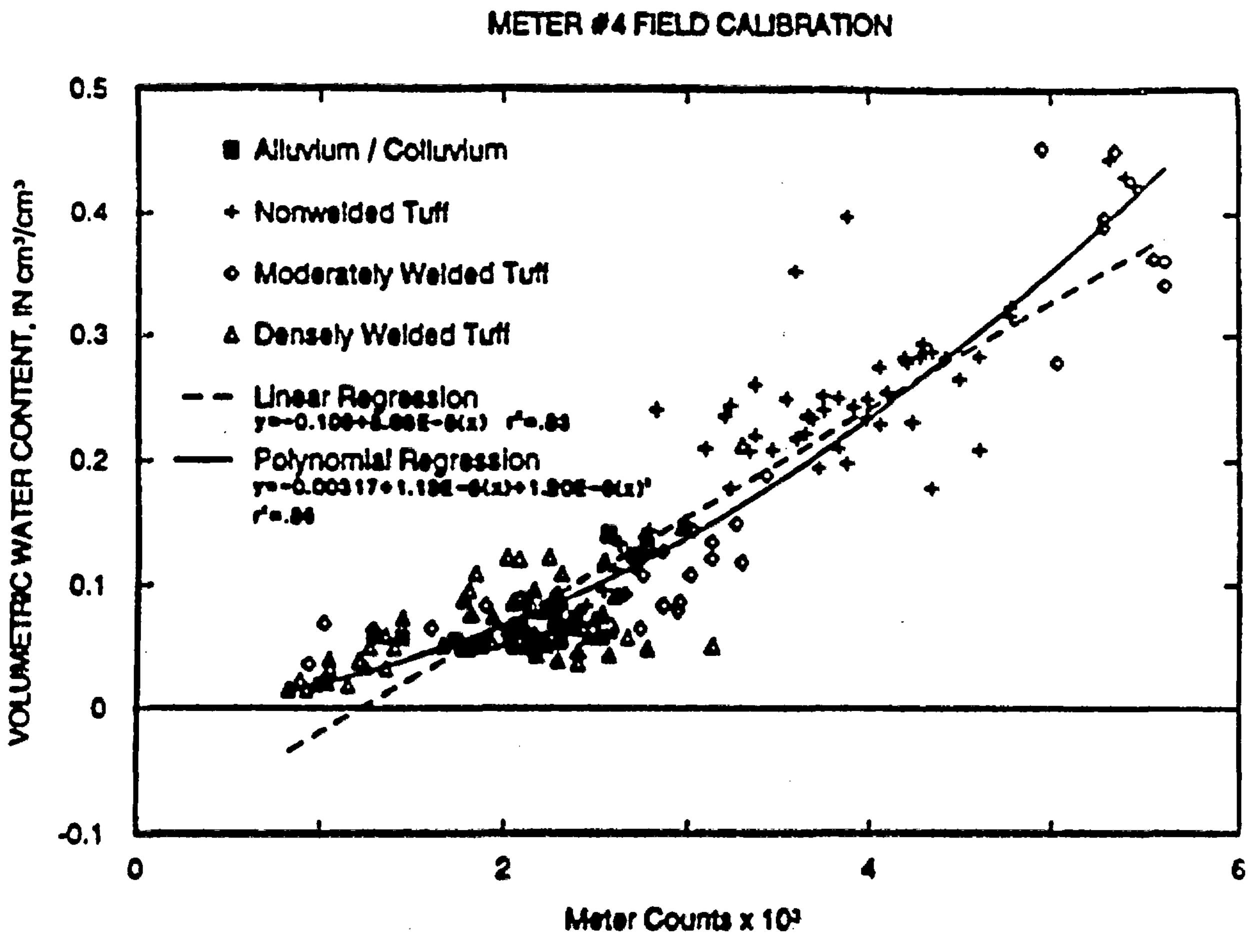


Figure 3.2-3. Diagram showing field calibrations of neutron-moisture meters from data in alluvium, nonwelded, moderately welded and densely welded tuff.

3.2.3.1.3.1 Location and depth of boreholes

The geohydrologic-surficial units are the basis for locating most of the neutron-access boreholes. The locations of boreholes (existing and proposed) are shown in Figures 3.2-4a and -4b. For each borehole (existing and proposed), the location, elevation, hole depth, depth of the tuff/alluvium contact, geohydrologic-surficial unit, and topographic position are listed in Table 3.2-1. It should be mentioned that some of the existing holes may yet be deepened to monitor natural infiltration at greater depths and supplement tritium profiling data. Also, the locations of some proposed holes may be changed as more information about natural infiltration becomes available and topographic locations are isolated that require additional information.

For most boreholes located in unconsolidated deposits, boreholes were drilled through the entire thickness of the deposit and at least 1 m (3 ft) into the underlying bedrock. Two holes terminate in the alluvium: UE-25 UZN #28 encountered a drilling problem; and, UE-25 UZN #85 was drilled to correlate borehole lithology with a nearby alluvial fan facies. Boreholes that begin in bedrock were generally drilled to 15 m (50 ft), which extend (7 m) beyond and initially assumed depth of net infiltration.

Some boreholes were located perpendicular to the main axis of a canyon. This is to examine how natural infiltration is affected by the thickness of the unconsolidated deposits, the proximity of the boreholes to the canyon walls, and the proximity of the borehole to the center of the most recently formed channels. Other boreholes were located parallel to the main canyon axis to study the effects of increased drainage area on infiltration. The boreholes in upland-bedrock geohydrologic units were located to cover the range of topography and soil thickness within each unit.

3.2.3.1.3.2 Borehole logging

Neutron-moisture logging has been an on-going activity since July, 1984. A USGS Technical Procedure (NWM-USGS-HP-62, R5, [see Table 3.2-5, p. 3.2-50]) describes the method for logging neutron-access boreholes.

Neutron-access boreholes are logged with portable Campbell Pacific Nuclear neutron-moisture meters. Initially, the holes were logged on a monthly schedule from July, 1984 to December, 1988 and more frequently after intense precipitation events likely to cause measurable infiltration. A review of the logging data showed that very small changes occurred in water content profiles when there was no precipitation. Therefore, it was decided to decrease

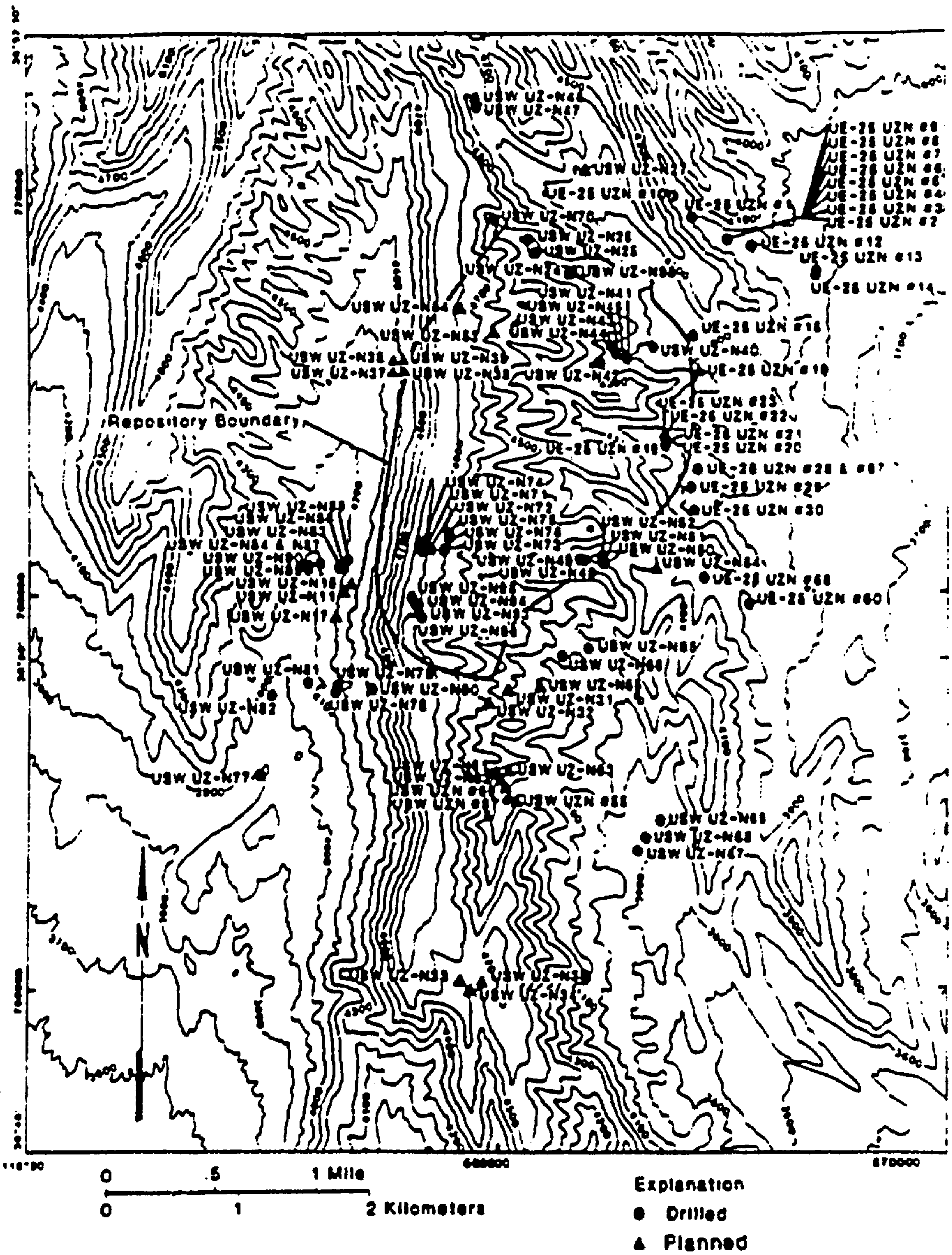


Figure 3.2-4a. Map showing neutron-access hole locations.

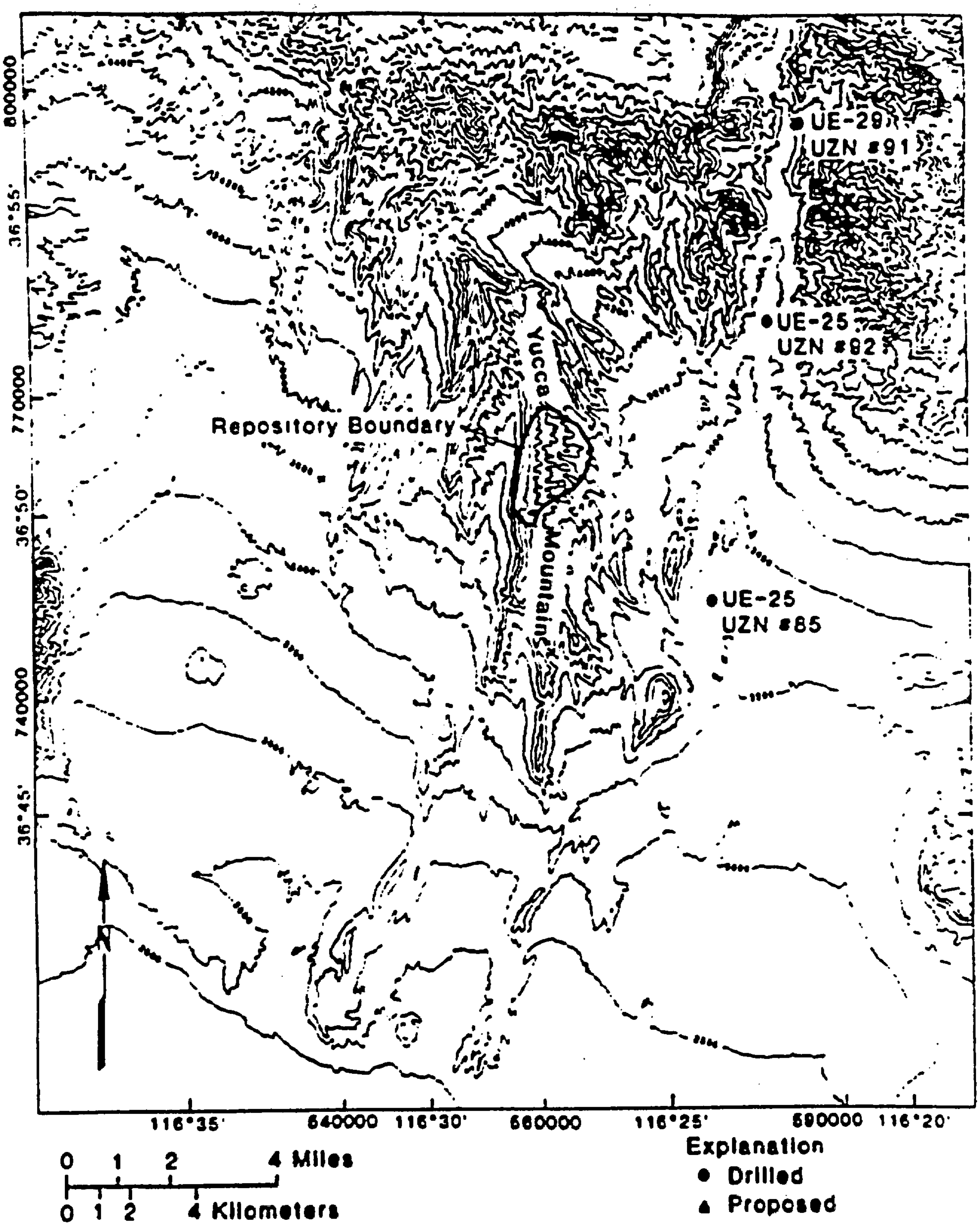


Figure 3.2-4b. Map showing neutron-access hole locations - Continued

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)
[ft, feet]

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| UE-25 UZN #1 | N 769,329 E 565,224 | 3,995 | 50 | 27.3 | Alluvium | Large-channel bottom |
| UE-25 UZN #2 | N 768,606 E 566,114 | 3,947 | 50 | 0.0 | Tiva Canyon lower lithophysal | Canyon wall |
| UE-25 UZN #3 | N 768,630 E 566,119 | 3,941 | 15 | 9.0 | Alluvium | Terrace |
| UE-25 UZN #4 | N 768,663 E 566,127 | 3,942 | 30 | 24.5 | " | Terrace |
| UE-25 UZN #5 | N 768,689 E 566,134 | 3,943 | 50 | 44.5 | " | Terrace |
| UE-25 UZN #6 | N 768,706 E 566,137 | 3,938 | 45 | 39.5 | " | Large-channel bottom |
| UE-25 UZN #7 | N 768,724 E 566,141 | 3,939 | 45 | 40.5 | " | Large-channel bottom |
| UE-25 UZN #8 | N 768,743 E 566,147 | 3,939 | 45 | 40.0 | " | Large-channel bottom |
| UE-25 UZN #9 | N 768,782 E 566,156 | 3,941 | 40 | 35.0 | " | Terrace |
| UE-25 UZN #10 | N 769,869 E 564,764 | 4,038 | 98.7 | 0.0 | Nonwelded and bedded tuffs | Large-channel |
| [1]USW UZ-N11 | N 760,000 E 556,400 | 4,260 | 50 | 3.0 [2] | Topopah Spring | Canyon wall |
| UE-25 UZN #12 | N 768,651 E 566,695 | 3,907 | 50 | 45.0 | Alluvium | Large-channel bottom |
| UE-25 UZN #13 | N 768,025 E 568,255 | 3,82° | 65 | 44.0 | " | Large-channel bottom |
| UE-25 UZN #14 | N 767,967 E 568,233 | 3,826 | 55 | 44.0 | " | Terrace |
| [1]USW UZ-N15 | N 760,000 E 556,400 | 4,260 | 50 | 0-3 [2] | Topopah Spring | Canyon wall |
| [1]UE-25 UZN #16 | N 765,700 E 565,400 | 3,990 | 50 | 0-10 [2] | Tiva Canyon clinkstone | Canyon wall |
| [1]USW UZ-N17 | N 759,400 E 556,000 | 4,200 | 50 | 3-6 [2] | Nonwelded and bedded tuffs | Canyon wall |
| UE-25 UZN #18 | N 766,472 E 565,247 | 4,019 | 61 | 56.0 | Alluvium | Large channel bottom |

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)--Continued
[ft, feet]

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| UE-25 UZN #19 | N 763,689 E 564,571 | 4,025 | 40 | 22.5 | Alluvium | Large-channel bottom |
| UE-25 UZN #20 | N 763,760 E 564,579 | 4,027 | 41 | 39.0 | Alluvium | Braided channel area |
| UE-25 UZN #21 | N 763,806 E 564,591 | 4,028 | 42 | 27.5 | Alluvium | Braided channel area |
| UE-25 UZN #22 | N 763,880 E 564,605 | 4,029 | 95 | 19.6 | Alluvium | Braided channel area |
| UE-25 UZN #23 | N 763,973 E 564,545 | 4,043 | 35 | 0.0 | Tiva Canyon lower lithophysal | Canyon wall |
| USW UZ-N24 | N 78,005 E 562,054 | 4,227 | 75 | 0.5 | Tiva Canyon hackley-columnar | Channel bottom |
| USW UZ-N25 | N 768,430 E 561,219 | 4,335 | 59 | 0.0 | Tiva Canyon hackley-columnar | Channel bottom |
| USW UZ-N26 | N 768,757 E 561,023 | 4,384 | 35 | 0.0 | Tiva Canyon lower lithophysal | Channel bottom |
| [1]USW UZ-N27 | N 770,780 E 562,500 | 4,500 | 50 | 0-3 [2] | Tiva Canyon hackley-columnar | Canyon wall |
| UE-25 UZN #28 | N 763,091 E 565,320 | 3,958 | 26.5 | ? | Alluvium | Braided channel |
| UE-25 UZN #29 | N 762,613 E 565,173 | 3,973 | 35 | 1.0 | Tiva Canyon clinkstone | Canyon wall dip slope |
| UE-25 UZN #30 | N 762,048 E 565,233 | 3,959 | 35 | 1.25 | Tiva Canyon clinkstone | Canyon wall dip slope |
| [1]USW UZ-N31 | N 757,400 E 559,900 | 4,400 | 50 | 0 [2] | Tiva Canyon clinkstone | Upland channel bottom |
| [1]USW UZ-N32 | N 757,100 E 559,900 | 4,610 | 50 | 0-1 [2] | Tiva Canyon upper lithophysal | Upper ridge dip slope |
| [1]USW UZ-N33 | N 752,000 E 558,200 | 4,850 | 50 | 0-1 [2] | Tiva Canyon caprock-upper cliff | Upland channel bottom |
| [1]USW UZ-N34 | N 750,100 E 558,100 | 4,770 | 50 | 0-1 [2] | Tiva Canyon upper lithophysal | Upland channel bottom |
| [1]USW UZ-N35 | N 749,800 E 558,200 | 4,730 | 50 | 0 | Tiva Canyon clinkstone | Upland channel bottom |
| [1]USW UZ-N36 | N 765,500 E 557,875 | 4,360 | 50 | 0-1.5 [2] | Tiva Canyon upper lithophysal | Canyon Wall |

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)--Continued
(ft, feet)

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| [1]USW UZ-N37 | N 765,125 E 557,875 | 4,360 | 50 | 0-0.5 [2] | Topopah Springs | Canyon wall |
| [1]USW UZ-N38 | N 765,125 E 558,000 | 4,380 | 50 | 0-3 [2] | Nonwelded and bedded tuffs | Canyon wall |
| [1]USW UZ-N39 | N 765,500 E 558,050 | 4,410 | 50 | 0-3 [2] | Nonwelded and bedded tuffs | Canyon wall |
| USW UZ-N40 | N 766,176 E 564,221 | 4,079 | 35 | 2.9 | Tiva Canyon lower lithophysal | Lower dip slope |
| USW UZ-N41 | N 765,867 E 563,521 | 4,118 | 37 | 16.0 | Alluvium | Channel bottom |
| USW UZ-N42 | N 765,729 E 562,859 | 4,179 | 40 | 0.0 | Tiva Canyon lower lithophysal | Channel bottom |
| USW UZ-N43 | N 765,997 E 563,264 | 4,149 | 45 | 27.0 | Alluvium | Terrace |
| USW UZ-N44 | N 766,193 E 563,140 | 4,162 | 36 | 0.0 | Tiva Canyon upper lithophysal | Channel bottom |
| USW UZ-N45 | N 765,977 E 563,429 | 4,130 | 45 | 35.5 | Alluvium | Channel bottom |
| USW UZ-N46 | N 772,262 E 559,748 | 4,501 | 90 | 0.0 | Nonwelded and bedded tuffs | Large-channel bottom |
| USW UZ-N47 | N 771,978 E 559,784 | 4,480 | 86.5 | 33.0 | Alluvium | Large-channel bottom |
| USW UZ-N48 | N 760,835 E 562,414 | 4,211 | 35 | 0.0 | Tiva Canyon hackley-columnar | Channel bottom |
| USW UZ-N49 | N 760,860 E 562,322 | 4,229 | 36 | 2.0 | Tiva Canyon clinkstone | Canyon wall dip slope |
| USW UZ-N50 | N 760,776 E 562,912 | 4,173 | 20 | 9.0 | Alluvium | Terrace |
| USW UZ-N51 | N 760,841 E 562,909 | 4,169 | 20 | 14.0 | Alluvium | Channel bottom |
| USW UZ-N52 | N 760,894 E 562,909 | 4,172 | 25 | 7.0 | Alluvium | Terrace |
| [1]USW UZ-N53 | N 766,730 E 560,875 | 4,640 | 50 | 0-1 [2] | Tiva Canyon upper lithophysal | Channel bottom |
| [1]USW UZ-N54 | N 760,700 E 564,300 | 4,080 | 50 | 0-3 [2] | Tiva Canyon clinkstone | Lower-ridge top dip slope |

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)--Continued
[ft, feet]

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| [1]USW UZ-N55 | N 757,500 E 561,600 | 4,250 | 50 | 0.-1.5 [2] | Tiva Canyon hackley-columnar | Lower-ridge top dip slope |
| UE-25 UZN #56 | N 760,394 E 565,480 | 3,960 | 60 | 56.0 | Alluvium | Channel bottom |
| [1]USW UZ-N57 | N 754,900 E 560,200 | 4,260 | 50 | 0 [2] | Topopah Spring | Canyon wall |
| [1]USW UZ-N58 | N 754,800 E 560,600 | 4,230 | 50 | 0-3 [2] | Topopah Spring | Channel bottom |
| [1]USW UZ-N59 | N 755,300 E 560,100 | 4,220 | 50 | 0-3 [2] | Nonwelded and bedded tuffs | Canyon wall |
| UE-25 UZN #60 | N 759,757 E 566,567 | 3,892 | 35 | 26.6 | Alluvium | Channel bottom |
| USW UZ-N61 | N 755,600 E 559,800 | 4,360 | 50 | 0-0.5 [2] | Tiva Canyon hackley-columnar | Canyon wall |
| USW UZ-N62 | N 755,400 E 560,200 | 4,280 | 50 | 0 [2] | Tiva Canyon hackley-columnar | Channel bottom |
| USW UZ-N63 | N 755,500 E 560,600 | 4,380 | 50 | 0 [2] | Tiva Canyon hackley-columnar | Canyon wall |
| [1]USW UZ-N64 | N 762,250 E 559,875 | 4,720 | 50 | 0-1.5 [2] | Tiva Canyon caprock-upper cliff | Upper-ridge dip slope |
| USW UZ-N65 | N 758,627 E 562,537 | 4,372 | 50 | 0.0 | Tiva Canyon caprock-upper cliff | Mid-ridge dip slope |
| USW UZ-N66 | N 758,434 E 561,881 | 4,356 | 50 | 0.0 | Tiva Canyon clinkstone | Mid-ridge dip slope |
| USW UZ-N67 | N 753,634 E 563,799 | 3,920 | 25 | 19.0 | Alluvium | Channel bottom |
| USW UZ-N68 | N 753,962 E 564,006 | 3,925 | 55 | 50.3 | Alluvium | Braided-channel area |
| USW UZ-N69 | N 754,461 E 564,402 | 3,918 | 35 | 27.0 | Alluvium | Channel bottom |
| USW UZ-N70 | N 769,251 E 560,165 | 4,542 | 35 | 0.0 | Tiva Canyon upper lithophysal | Channel bottom |
| USW UZ-N71 | N 761,026 E 558,406 | 4,925 | 52 | 0.0 | Tiva Canyon caprock-upper cliff | Upper-ridge dip slope |
| USW UZ-N72 | N 761,068 E 558,626 | 4,889 | 30 | 0.0 | Tiva Canyon caprock-upper cliff | Upland channel bottom |

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)--Continued
[ft, feet]

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| USW UZ-N73 | N 761,049 E 558,926 | 4,867 | 30 | 0.0 | Tiva Canyon upper lithophysal | Upland channel bottom |
| USW UZ-N74 | N 761,362 E 558,560 | 4,906 | 37 | 0.0 | Tiva Canyon caprock-upper cliff | Upper-ridge dip slope |
| USW UZ-N75 | N 761,462 E 559,076 | 4,799 | 37 | 2.0 | Tiva Canyon caprock-upper cliff | Upper-ridge dip slope |
| USW UZ-N76 | N 761,353 E 559,048 | 4,958 | 35 | 0.0 | Tiva Canyon upper lithophysal | Upper-ridge dip slope |
| USW UZ-N77 | N 755,526 E 554,397 | 3,901 | 50 | 38.0 | Alluvium | Large-channel bottom |
| USW UZ-N78 | N 757,558 E 556,262 | 4,182 | 30 | 0.0 | Tiva Canyon caprock-upper cliff | Canyon wall |
| USW UZ-N79 | N 757,733 E 556,334 | 4,155 | 32 | 0.0 | Tiva Canyon upper lithophysal | Channel bottom |
| USW UZ-N80 | N 757,634 E 557,201 | 4,332 | 52 | 0.0 | Topopah Spring | Upland channel bottom |
| USW UZ-N81 | N 757,807 E 555,595 | 4,065 | 70 | 6.0 | Alluvium | Channel bottom |
| USW UZ-N82 | N 757,498 E 554,690 | 3,975 | 40 | 22.1 | Alluvium | Large-channel bottom |
| USW UZ-N83 | N 760,624 E 556,349 | 4,157 | 70 | 0.0 | Tiva Canyon upper lithophysal | Small-channel bottom |
| USW UZ-N84 | N 760,717 E 555,888 | 4,112 | 45 | 20.1 | Alluvium | Terrace |
| UE-25 UZN #85 | N 750,716 E 577,568 | 3,337 | 80 | ? | Alluvium-colluvium | Terrace |
| USW UZ-N86 | N 760,615 E 556,460 | 4,172 | 30 | 0.0 | Tiva Canyon caprock-upper cliff | Small-channel bottom |
| USW UZ-N87 | N 760,714 E 555,887 | 4,112 | 45 | 19.0 | Alluvium | Terrace |
| USW UZ-N88 | N 760,797 E 556,551 | 4,202 | 30 | .76 | Tiva Canyon upper lithophysal | Canyon wall |
| USW UZ-N89 | N 760,610 E 555,589 | 4,090 | 45 | 33.0 | Alluvium | Large-channel bottom |
| USW UZ-N90 | N 760,608 E 555,587 | 4,090 | 45 | 32.7 | Alluvium | Large-channel bottom |

Table 3.2-1. Drilling and geologic summary of the neutron-access holes at Yucca Mountain (SCP 8.3.1.2.2.1.2)--Continued
(ft, feet)

| Hole number | Nevada central coordinates (ft) | Elevation (ft) | Hole depth (ft) | Alluvium tuff contact (ft) | Preliminary geohydrologic-surficial unit | Topographic setting |
|---|---|---|---|---|---|---|
| UE-25 UZN #91 | N 797,275 E 585,341 | 3,669 | 94 | 69.0 | Alluvium | Large-channel bottom |
| UE-25 UZN #92 | N 778,010 E 583,559 | 3,669 | 120 | 58.0 | Alluvium | Large-channel bottom |
| USW UZ-N93 | N 759,584 E 558,321 | 4,924 | 40 | 0.0 | Tiva Canyon caprock-upper cliff | Disturbed area |
| USW UZ-N94 | N 759,724 E 558,236 | 4,926 | 30 | 0.0 | Tiva Canyon caprock-upper cliff | Disturbed area |
| USW UZ-N95 | N 759,899 E 558,172 | 4,929 | 20 | 0.0 | Tiva Canyon caprock-upper cliff | Disturbed area |
| USW UZ-N96 | N 759,446 E 558,403 | 4,893 | 35 | 2.0 | Tiva Canyon caprock-upper cliff | Disturbed area |
| UE-25 UZN #97 | N 763,094 E 565,321 | 3,958 | 0 | 52.0 | Alluvium-colluvium | Braided channel area |
| USW UZ-N98 | N 767,992 E 562,084 | 4,223 | 75 | 1.0 | Tiva Canyon Hackley-columnar | Channel bottom |

[1] Proposed drill holes
[2] Estimated unconsolidated soil or rock cover

logging frequency to a bimonthly schedule, and increase frequency following major precipitation events.

Because hole conditions have an effect on neutron-moisture meter readings, a density log will be run in each hole. The density profile will provide information about hole rugosity and changes in formation density. New calibrations will be generated when new boreholes are drilled on Yucca Mountain and additional data becomes available.

3.2.3.1.3.3 Monitoring and analysis

A comparison of water profiles (from adjacent boreholes located adjacent and within the wash) measured before and after intense precipitation events can yield a qualitative picture of water content change in the surficial materials penetrated by the borehole. For example, water-content profiles measured over a nine-month period are illustrated for one borehole located in the center of a stream channel on alluvium and another located approximately 9 m (30 ft) away on an alluvium terrace, (Figures 3.2-5 and 3.2-6). Approximately 80 mm (3 in.) of rain fell on the area during an intense thunderstorm on August 19, 1984. Runoff occurred, and the channel was partially filled with water for a short period of time (probably less than one hour). The water level in the channel did not rise high enough to reach the neutron-access borehole located on the adjacent terrace.

Note that, immediately after the rainfall, there was a large increase in water content at the upper part of the borehole located in the channel (UE-25 UZN Ø13). This increased water content near the land surface decreased over time, and water contents at greater depths increased slowly. The decrease in water contents near the surface (5/14/85 profile) was due to a combination of upward movement (evapotranspiration), and percolation of water (lateral movement may also be a component). The increase in water contents at the greater depths over a period of months was most likely a result of water moving downward.

It should be emphasized that the water contents shown in these profiles may not be true or absolute values. The calibration curves (Figure 3.2-3) have been generated for materials with an average bulk density of approximately 1.65 g/cm³. Because the alluvium is a heterogeneous mixture of particle sizes, ranging from boulders to silt-size materials, it is possible that the neutron-moisture tools may be sensing solid boulders of densely welded tuff with bulk densities of greater than 2.25 g/cm³ at some depths. As calibration curves are known to depend on bulk density, water contents in boulder zones will not be absolute values. Fortunately, the absolute values of water content are not of

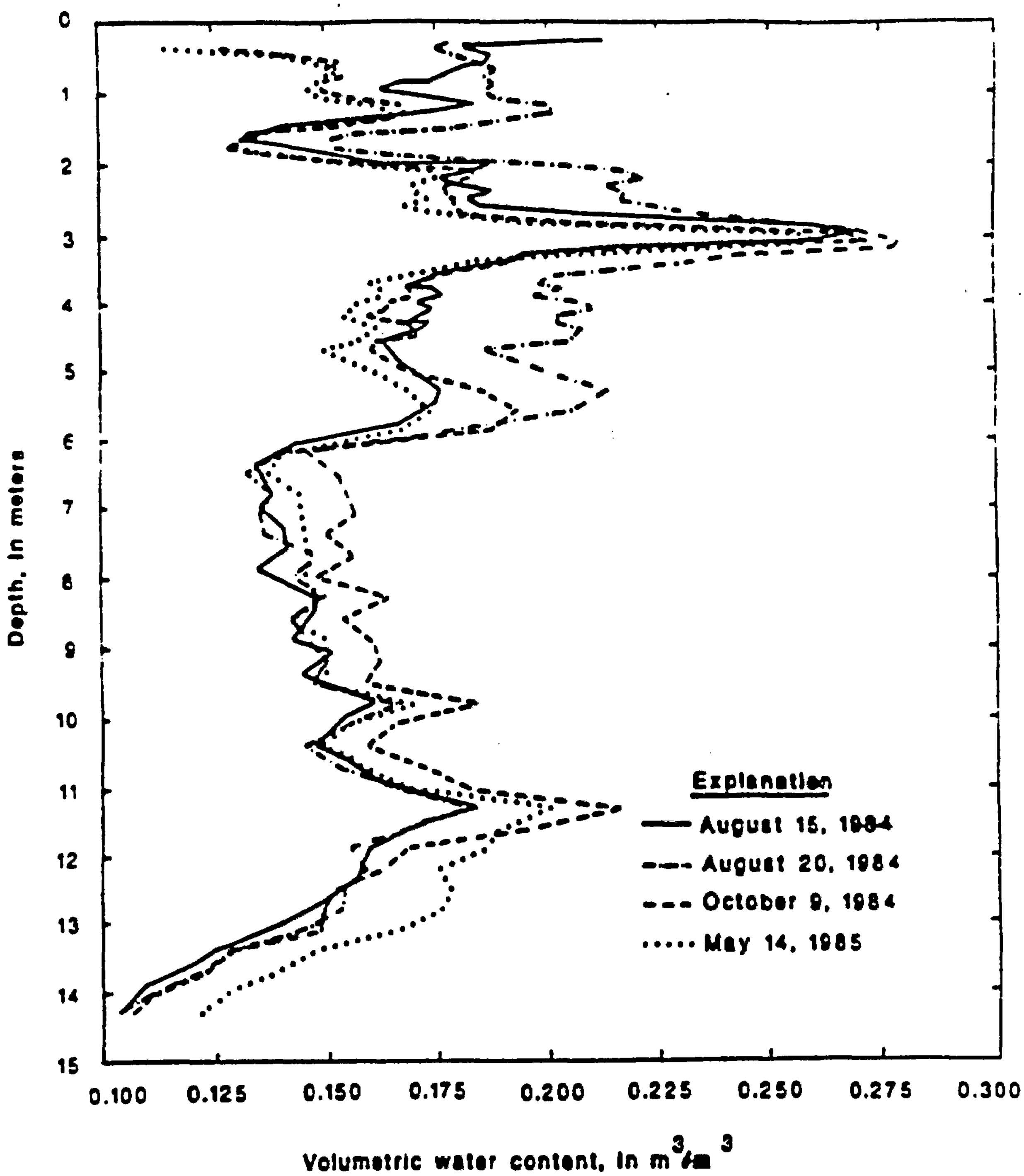


Figure 3.2-5. Diagram showing substantial changes in water-content profiles for UE25 UZN13 located in center of Pagany Wash.

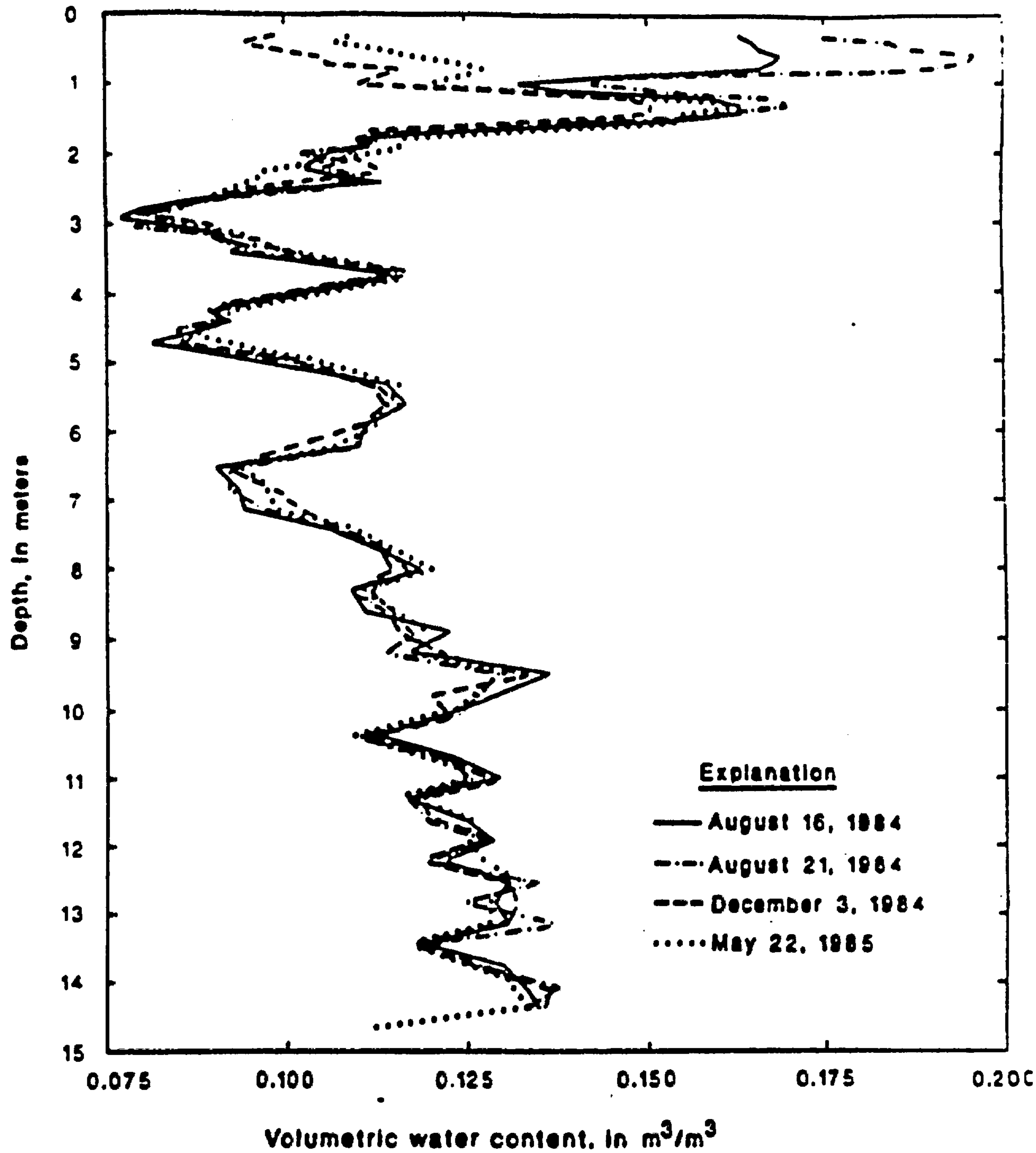


Figure 3.2-6. Diagram showing minor changes in water-content for UE-25 UZN14 located on terrace adjacent to UE-25 UZN13 in Pagany Wash.

critical importance in the quantitative analysis of moisture-logging data. The difference between water-content profiles, however, is of central importance. The area between consecutive water-content profiles for a given depth interval is a quantitative measure of the volume of water that has flowed into or out of that depth interval via nonsteady-state flow processes. Even the relative differences can be in error if the calibration equation that was used differs from the "real" equation, particularly if a density dependent quadratic equation is necessary.

An analysis was performed on water-content data collected in August, 1984 in the neutron-access holes that were located across Pagany Wash. Figure 3.2-7a displays the water content immediately before the storm. The neutron holes were logged again 24 hours, 48 hours, and several months after the end of the precipitation and runoff event. Differences in water contents between the post-storm and pre-storm profiles are presented in Figure 3.2-7b. Water content increased 0.02 $cm^3/cm^3$, 4.6 m (15 ft) into the alluvial channel within 24 hours (averaging $5.32 * 10^{-5}$ m/s vertical velocity). There was a maximum increase in water content of 0.08 $cm^3/cm^3$, 1.5 m (5 ft) from the surface. The neutron holes were logged again 48 hours later and the difference between that log and the pre-storm log is presented in Figure 3.2-7c. The overall reduction in water content is most likely due to evapotranspiration and subsurface water flow downstream. There should be an equilibration of water flowing out of the area downstream as water flowing into the area from upstream. Further analysis and modeling of this data is currently underway. Figure 3.2-7d shows the difference in water content between the maximum and minimum ever recorded between 1984 and 1989. It can be seen that the first post-storm logging was the maximum water ever recorded within the top 15 feet (compare Figures 3.2-7b and 3.2-7d). There are indications that the water content changes at greater depth are most likely due to percolation and upstream water flow into the area. These data represent an exception to most other neutron data collected over the last 5 years. Most data shows little change ($<0.02$ $cm^3/cm^3$) at depths greater than 3 to 4 meters. Changes of $<0.01$ $cm^3/cm^3$ are assumed to be due to random fluctuations in neutron counts obtained during logging.

### 3.2.3.2 Monitoring of natural infiltration in artificial-infiltration, control-plot studies

Natural infiltration will also be monitored intensively in the control plots associated with small- and large-plot rainfall simulations (Sections 3.3.3.3 and 3.3.3.4). These control plots will serve two main purposes. First, they will provide information on the response of the soil profile to the natural inputs at a given artificial-infiltration site. This information will be used in interpreting the artificial-infiltration data. Second, and most

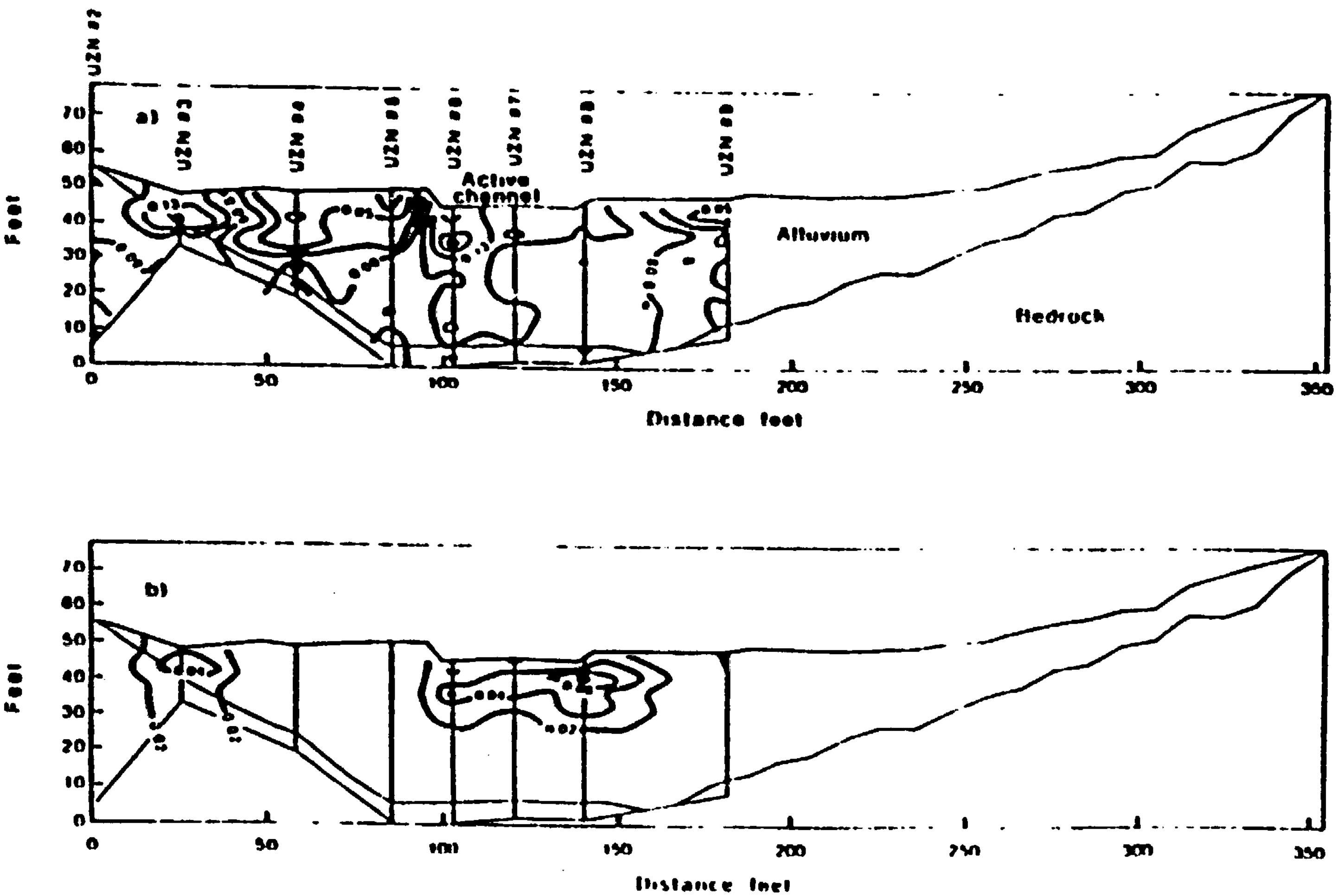


Figure 3.2-7a,b Diagram showing water content (cm³/cm³) determined using neutron moisture meter in 8 boreholes in Pagany Wash in August, 1984. a) Pre-storm water content. b) differences between pre-storm water content and 24 hour post-storm water content.

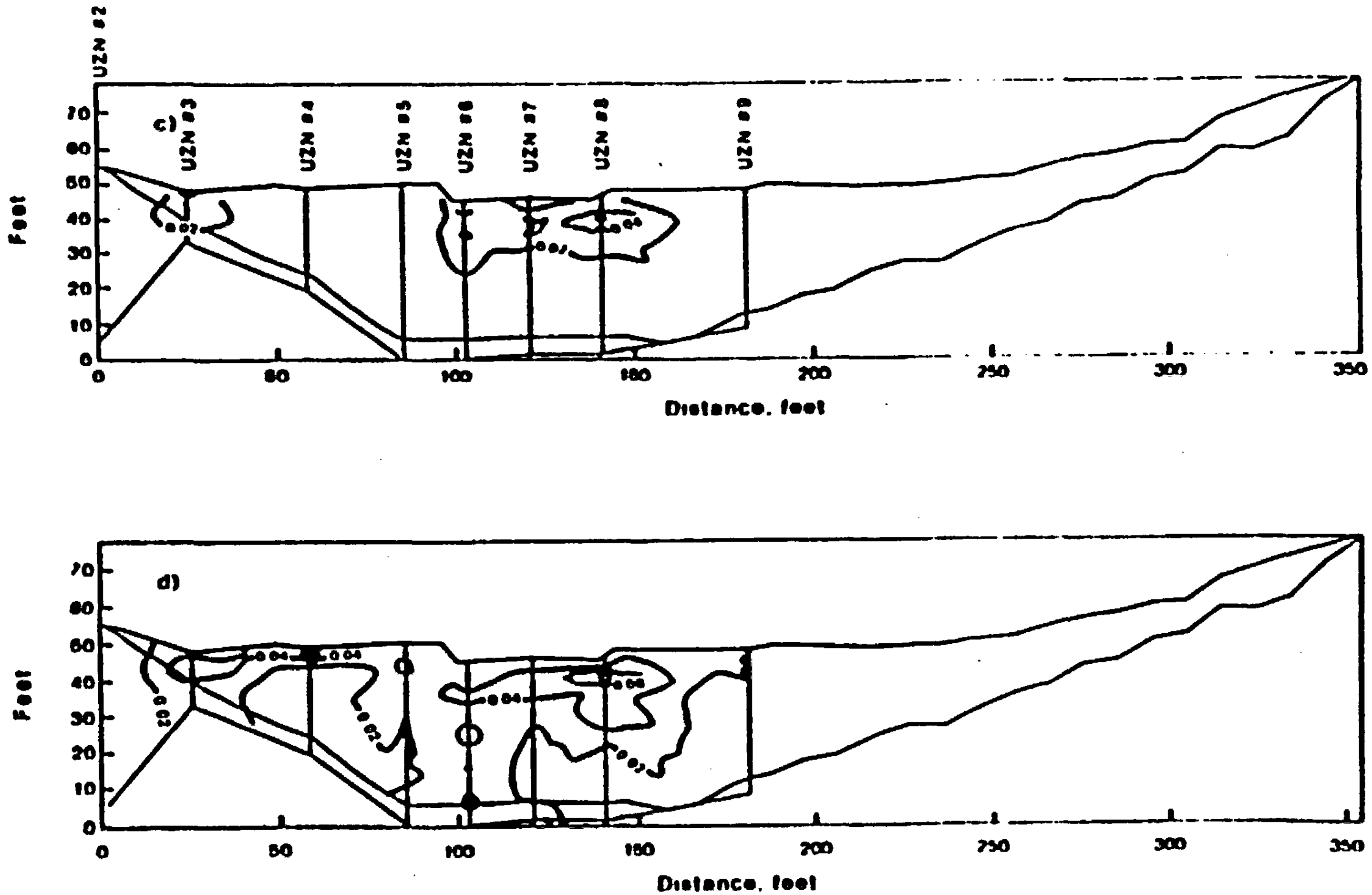


Figure 3.2-7c,d. Diagram showing water content (cm³/cm³) determined using neutron-moisture meter in 8 boreholes in Pagany Wash c) Difference between pre-storm water content and 48 hour post-storm water content, August, 1984, and d) difference in water content between the maximum and minimum recorded between 1984 and 1989

importantly, they will serve as sites where the most intensive monitoring of natural infiltration will be done.

It is expected that some of the most useful natural-infiltration data will come from the control plots since many more parameters beyond just water content are to be measured. These additional parameters include water potential, bulk density, porosity, evapotranspiration, and atmospheric conditions. The values and distributions of these parameters will not only permit numerical simulations to be conducted, but will also allow analytical techniques to be applied over discrete time periods to compute natural infiltration. Site parameters and data collection methods listed in Table 3.2-4 (p. 3.2-45) will be described in more detail in Sections 3.3.3.3 and 3.3.3.4.

### 3.2.3.3 Tritium-profiling studies

Large amounts of tritium were released into the atmosphere during the period of large-scale thermonuclear atmospheric bomb testing between 1952 and 1962. As a result of precipitation, some of this tritium has entered the hydrologic cycle as tritiated water. The input of bomb-produced tritium to the unsaturated zone has resulted in tritium concentrations which are higher than natural background levels and, hence, make tritium an excellent environmental tracer (Freeze and Cherry, 1979). Natural background concentrations are generally less than 10 Tritium Units (TU)(1 TU = 1 tritium atom in $10^{18}$ atoms of hydrogen or 0.118 Bq $Kg^{-1}$)(Phillips and others, 1988). Although Yucca Mountain is located on the NTS, there is no evidence to suggest anomalies in tritium fallout due to nuclear weapons testing. Further analysis of tritium or other radioactive tracers (USGS-SP 8.3.1.2.2.7) will be done with the location of Yucca Mountain on the western boundary of the NTS in mind.

Samples from several boreholes located on different geohydrologic surficial materials were collected for initial tritium-concentration profiling. Most of the boreholes from which samples were collected penetrate high-porosity (>0.25) materials (alluvium and/or nonwelded and bedded tuff) where matrix flow is expected to dominate. Furthermore, the volumetric-water content in these rocks was large enough to make it possible to extract sufficient water for tritium analysis. Several boreholes which penetrate low-porosity welded tuff, where fracture flow was expected to dominate, were also selected to evaluate the range of geohydrologic conditions in which tritium profiling could be used successfully. These tuff samples with small values of porosity also were selected to determine if it is possible to extract enough water to do tritium analyses. Borehole, rock, and sample information as well as preliminary results are summarized in Table 3.2-2. Preliminary sample testing for tritium was done at the USGS Stable Isotope Laboratory in Reston, Virginia.

Water was extracted from core samples by a vacuum distillation and condensation procedure. Tritium concentration in the water

Table 3.2-2. Summary of preliminary, completed, and planned tritium analyses (SCP 8.3.1.2.2.1.2)
(ft, feet; ft/year; feet per year)

| Borehole number | Geohydrologic units penetrated | Topographic position | Depth to bedrock (ft) | Depth interval analyzed (ft) | Number of samples to be analyzed core/cuttings | | Max. depth reached by bomb tritium (ft) | Est. average flow velocity (ft/year) |
|---|---|---|---|---|---|---|---|---|
| UE-25 UZ-4 | Alluvium | Channel bottom | 39.5 | 3.0 - 38.5 | 12 | 0 | 16.5 | -0.56 |
| UE-25 UZN #8 | " | " | 40.0 | 10.0 - 37.0 | 7 | 0 | 25.0 | 0.83 |
| USW UZ-7 | " | " | 22.0 | 6.25 - 21.75 | 4 | 0 | >21.75 | >0.73 |
| USW UZ-N90 | " | " | 35.0 | 2.0 - 32.5 | 6 | 0 | 9.5 | 0.32 |
| UE-25 UZN #1 | " | " | 25.5 | 7.25 - 26.5 | 4 | 0 | >26.5 | >.88 |
| UE-29 UZN #91 | " | " | 69.0 | 10.0 - 69.0 | 13 | 0 | | |
| UE-25 UZN #92 | " | " | 58.0 | 0.0 - 102.0 | 16 | 0 | | |
| UE-25 UZN #85 | " | High terrace | - | 3.3 - 78.7 | 15 | 0 | | |
| UE-25 UZN #21 | " | Low terrace | 27.5 | 1.25 - 26.5 | 6 | 0 | | |
| UE-25 UZN #10 | Nonwelded and bedded | Channel bottom | 0.0 | 1.3 - 91.7 | 18 | 4 | | |
| USW UZ-N24 | Moderately-columner/nonwelded | " | 0.0 | 7.5 - 75.0 | 14 | 14 | | |

Table 3.2-2. Summary of preliminary, completed, and planned tritium analyses (SCP 8.3.1.2.2.1.2)--Continued
(ft, feet; ft/year; feet per year)

| Borehole number | Geohydrologic units penetrated | Topo-graphic position | Depth to bedrock (ft) | Depth interval analyzed (ft) | Number of samples to be analyzed core/cuttings | Max. depth reached by bomb tritium (ft) | Est. average flow velocity (ft/year) |
|---|---|---|---|---|---|---|---|
| USW UZ-N40 | Lower lithophysal | Channel bottom | 0.0 | 6.0 - 32.5 | 6 4 | | |
| UE-25 UZN #29 | Clinkstone | Lower ridge dip slope | 10.0 | 0.5 - 26.4 | 6 7 | | |
| USW UZ-N70 | Upper lithophysal | Channel bottom | 0 | 7.8 - 34.0 | 6 6 | | |
| USW UZ-N74 | Caprock-upper cliff | Upper ridge dip slope | 0 | 5.0 - 35.6 | 3 4 | | |
| USW UZ-6s | All preliminary hydrogeologic units | Ridge top | 0 | 8.0 - 481.6 | 8 13 | | |

sample was then determined by standard scintillation techniques. The resulting tritium concentrations from the five boreholes were plotted as a function of depth in Figures 3.2-8a, b, c, d and e. Along with the tritium data, water content obtained from neutron-logging data is plotted, which is the difference between the maximum and the minimum volumetric-water content values ever observed at each depth between 1984 and 1988. There is a simple visual correlation between the maximum change in water content and the higher tritium concentrations. Although there has been little analysis on this recent data it has been included to show the correlation. Granted that the tritium samples were collected while drilling the boreholes and the neutron logs were collected after drilling the boreholes, the correlation indicates that the process occurring over the last four to five years is similar to the process occurring for the last 20-30 years. Since the shallow concentration peaks appear at about the same depth as the greater water-content changes. A large quantity may be moved through the liquid phase. This does not negate the influence of vapor-phase transport which will be considered throughout the study.

In three of the cases (Figures 3.2-8a, c, and d) there appears to be a good correlation between the decrease in tritium and a decrease in the difference between maximum and minimum water content for a given depth.

The background tritium (<10 TU) corresponds to a maximum difference in water content at approximately 0.03 $cm^3/cm^3$. It may be that this apparent change in water content is an artifact of the nuclear logging and not a real change in water content. Further investigation of this relationship is necessary.

There is no apparent explanation for the low tritium value at 2 m in Figure 3.2-8b, although the next three tritium data points seem to be in agreement with the other data (Figure 3.2-8a, b, and c). The increase in water content and tritium in Figure 3.2-8e at the alluvium-bedrock interface may indicate the presence of lateral flow along the contact. There has been a higher volume of water between 7 and 8 m than between 6 and 7 m which indicates a non-vertical flow path. Further analysis of this data, supplemented by new data and models of this system is required.

Average water-flow velocities were calculated from the depth to which concentration peaks occurred and the time elapsed from the midpoint in the period of above-ground testing (approximately 30 years). Preliminary velocity values summarized in Table 3.2-2 indicate that average flow velocities beneath alluvium-colluvium filled channels at Yucca Mountain range from 0.1 m/yr (0.32 ft/yr, $3.17 * 10^{-7}$ cm/s) to greater than 0.3 m/yr (0.88 ft/yr, $9.51 * 10^{-7}$ cm/s), depending upon borehole location.

From Section 3.2.3.1.3.3, (Figure 3.2-7b), it is apparent that water can move quickly under certain circumstances and that calculating average velocities is likely to be inappropriate. It is quite possible that the tritium detected at depth may have resulted

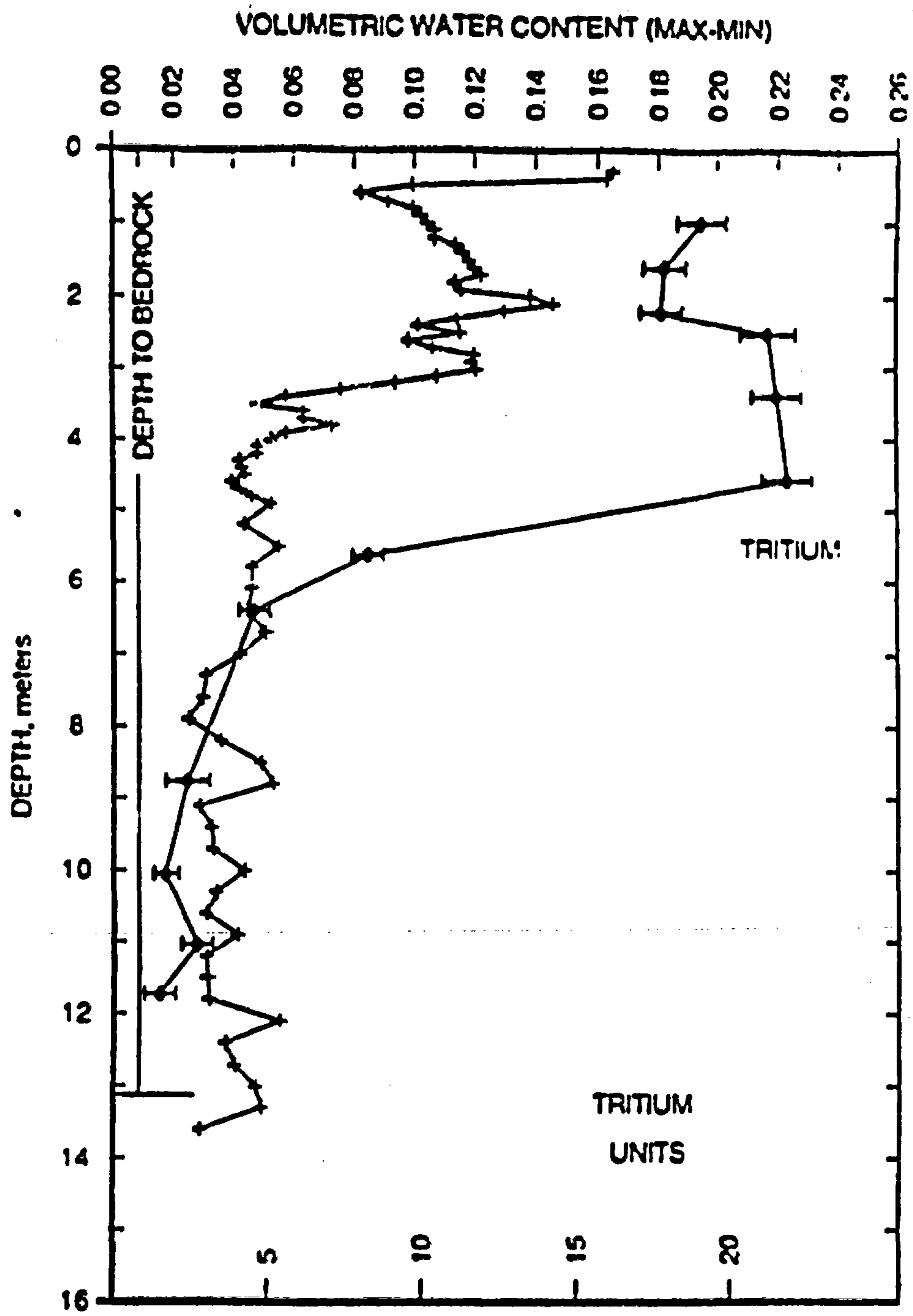


**Figure 3.2-8a. Diagram showing tritium concentration from borehole UE-25 UZ-4 and calculated mean of the maximum minus minimum volumetric-water content from two nearby boreholes between 1984 and 1988, plotted as functions of depth. Magnitude of error bars are equal to +/- the measurement errors submitted by the analytical laboratory.**

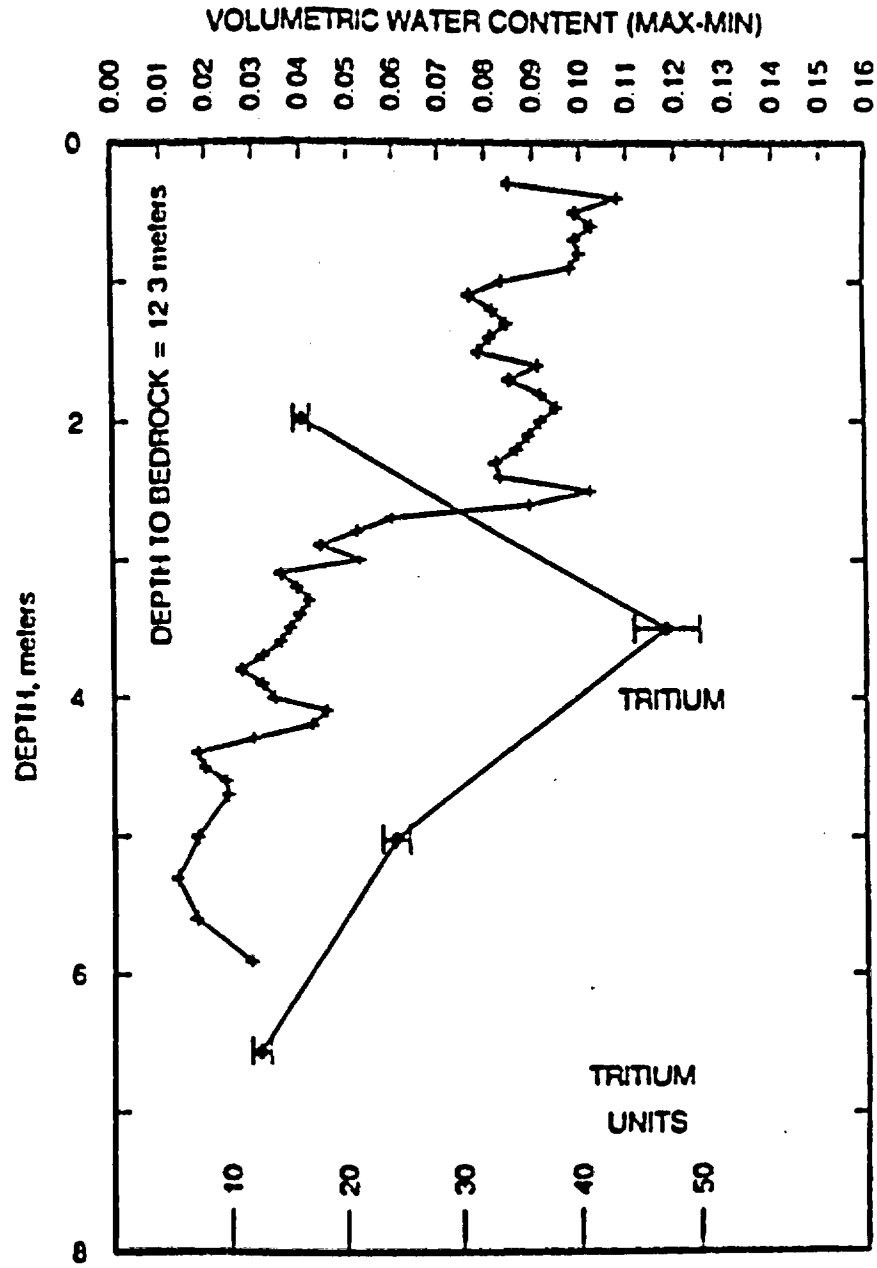


Figure 3.2-8b. Diagram showing tritium concentration from borehole UE-25 UZ-7 and calculated mean of the maximum minus minimum volumetric-water content from two nearby boreholes between 1984 and 1988, plotted as functions of depth. Magnitude of error bars are equal to +/- the measurement errors submitted by the analytical laboratory.

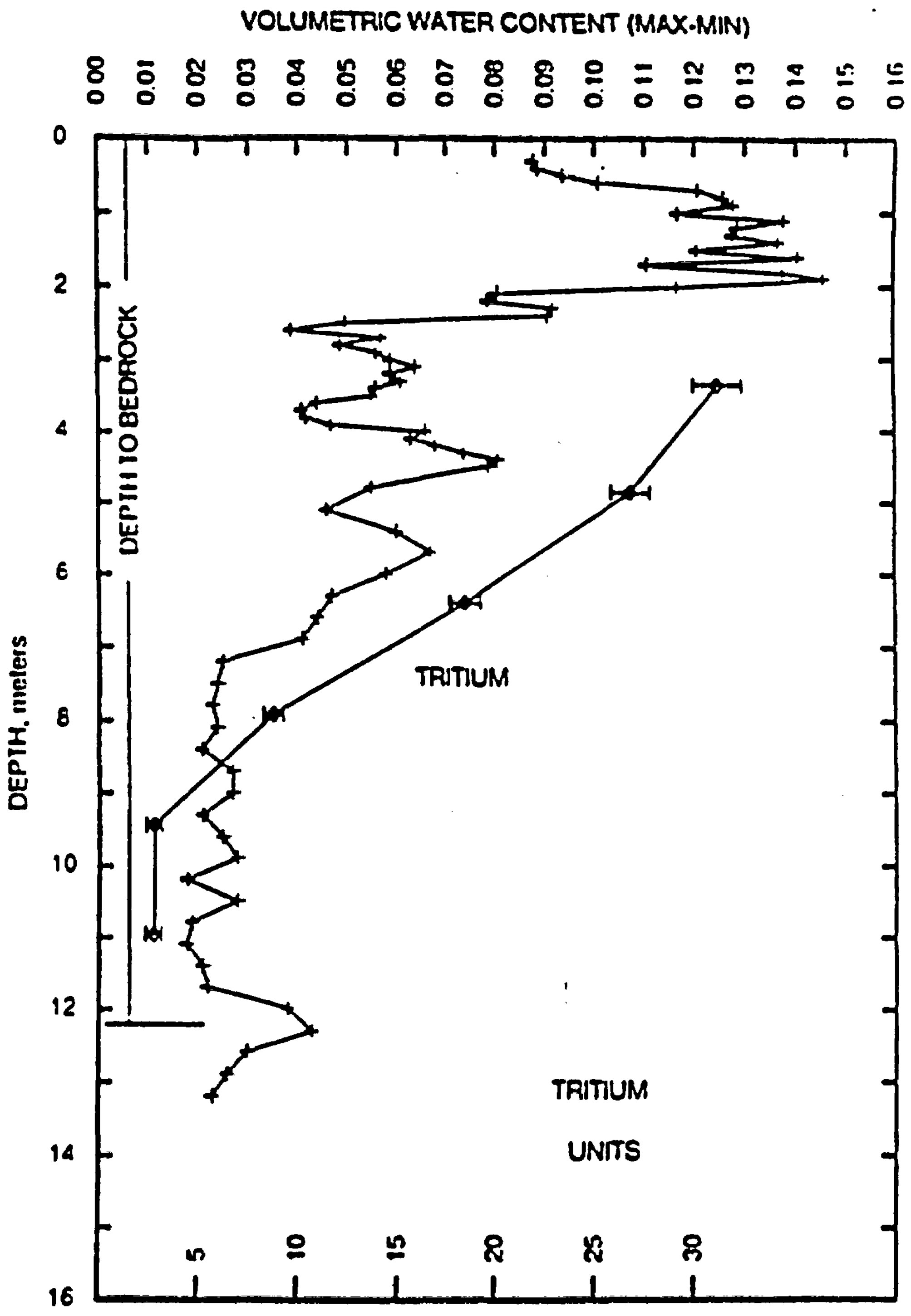


Figure 3.2-8c. Diagram showing tritium concentration and maximim minus minimum volumetric-water content between 1984 and 1988, plotted as functions of depth from borehole UE-25 UZN #8. Magnitude of error bars are equal to +/- the measurement errors submitted by the analytical laboratory

## *ABSTRACT*

This study plan describes the plans for three site-characterization activities to be performed on and adjacent to Yucca Mountain, Nevada. These activities will contribute to an understanding of hydrologic properties of surficial materials (soil and exposed bedrock) and an evaluation of natural- and artificial-infiltration processes in the near-surface unsaturated zone. Results from these activities will provide hydrologic-parameter input for the resolution of design and performance issues. These activities include:

- o Characterization of hydrologic properties of surficial materials,
- o Evaluation of natural infiltration, and
- o Evaluation of artificial infiltration.

The rationale for the unsaturated-zone infiltration study is described in Sections 1 (regulatory rationale) and 2 (technical rationale). Section 3 describes the specific activity plans, including the tests and analyses to be performed, the selected and alternate methods considered, and the technical procedures to be used. Section 4 summarizes the application of the study results and Section 5 presents the schedules and associated milestones.

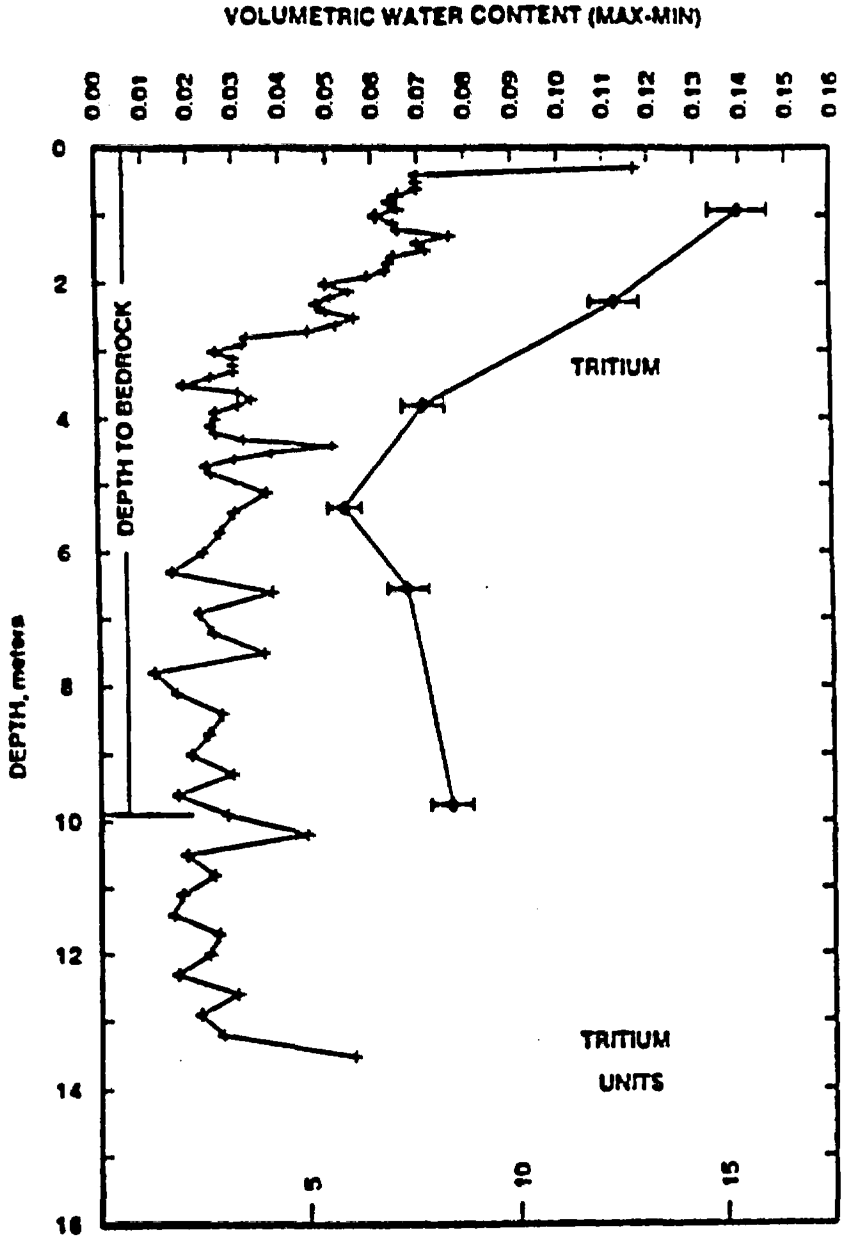


Figure 3.2-8d. Diagram showing tritium concentration and maximim minus minimum volumetric-water content between 1984 and 1988, plotted as functions of depth from borehole UE-25 UZN #90. Magnitude of error bars are equal to +/- the measurement errors submitted by the analytical laboratory.

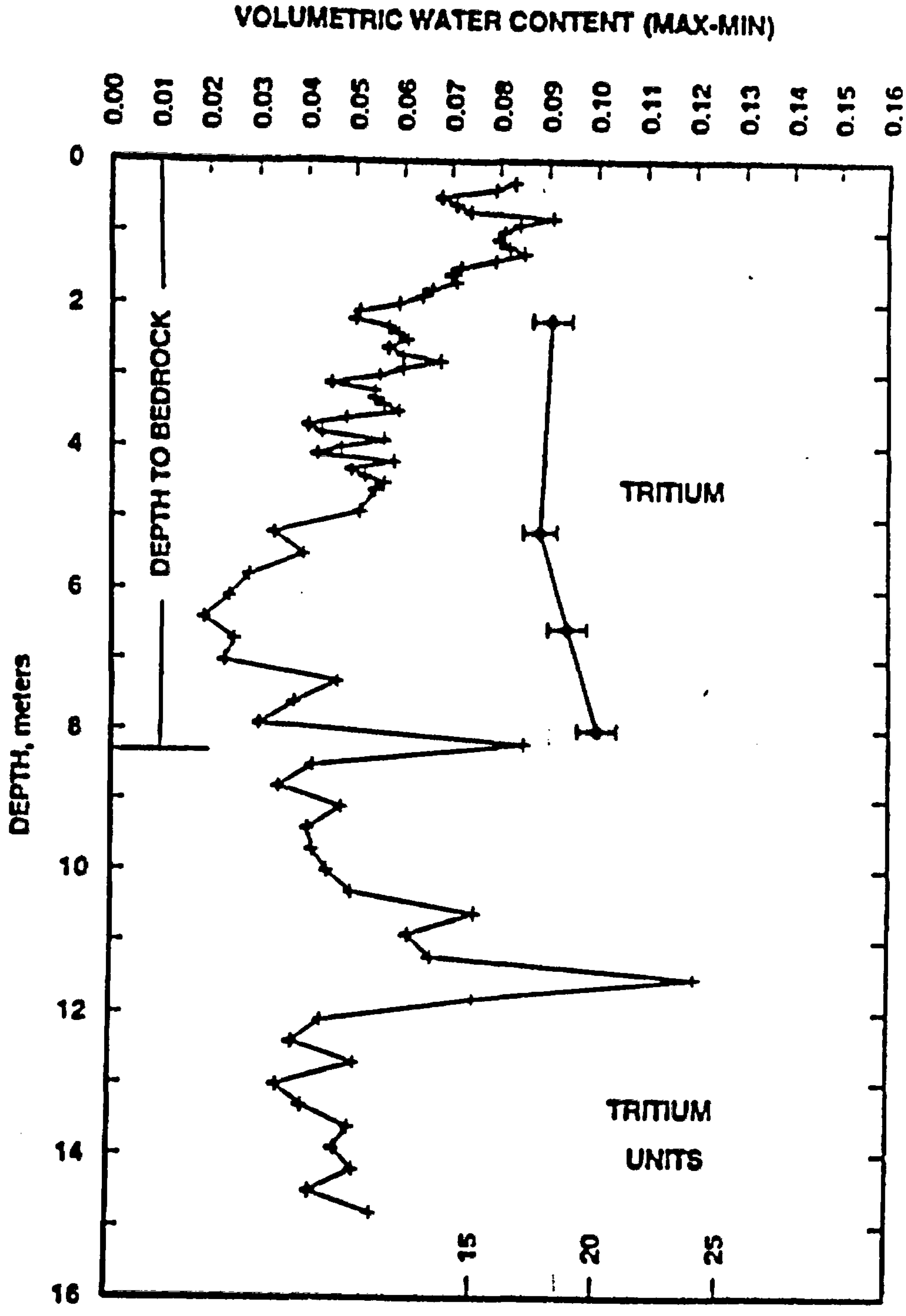


Figure 3.2-8e. Diagram showing tritium concentration and maximum minus minimum volumetric-water content between 1984 and 1988, plotted as functions of depth from borehole UE-25 UZN #1. Magnitude of error bars are equal to +/- the measurement errors submitted by the analytical laboratory

from one or two specific precipitation events prior to neutron logging since the core were taken before any neutron logging was completed. Other tritium data from UE-25 UZ-4 indicates several additional peaks of tritium at greater depths (Study 8.3.1.2.2.8). Since there also is an indication of older water overlying modern water (tritiated), there is lateral flow reaching the deeper unsaturated zone that is not going through the deeper part of the wash at UE-25 UZ-4. The possibility of lateral transfer of water between units will be investigated in this and other studies.

A numerical model that uses the Newton-Raphson method of solution of the convection-dispersion solute transport equations (Campbell, 1985) will be used to simulate the tritium-concentration profiles. From this analysis, hydraulic-conductivity values will be estimated and compared to the hydraulic-conductivity values of the matrix and the alluvium obtained from other studies. This may provide additional information as to the relative importance of matrix versus fracture flow. Concentration peaks occurring at deeper depths may be attributed to fracture flow.

The partially-completed tritium analyses indicate that bomb-tritium profiles can be successfully constructed for alluvium-colluvium-filled channels at Yucca Mountain. Additional samples of cuttings and core from the preliminary selections are currently being tested for tritium (Table 3.2-2). When these analyses are completed, the analytical results will be used to determine which additional boreholes should be tested for tritium concentrations. It is apparent that further tritium analysis will be required in the characterization of infiltration processes. Samples will be collected from all additional neutron holes for analysis. At that time the historical tritium data and the most recent data will be combined and analyzed and correlated with tritium analysis collected under SP 8.3.1.2.2.7 (Characterization of the unsaturated-zone hydrochemistry). This information may be essential in better defining the conceptual model of infiltration as described in Section 2.1.3.

### 3.2.3.4 Water-budget studies

Water-budget studies will be used to estimate net infiltration using the mass-balance approach. This approach will give qualitative and quantitative descriptions of the near-surface hydrologic system at Yucca Mountain. Data collection procedures described in this section will be carried out in conjunction with Study 8.3.1.2.1.1 (Characterization of the meteorology for regional hydrology). A more detailed listing of the tests and methods for site parameters mentioned here is provided in that study.

#### 3.2.3.4.1 Approach and hypotheses

The simplest form of the water-balance equation is:

$$I = [ P - R - ET ] + \Delta S$$

where I = net infiltration, P = precipitation, R = surface runoff, ET = evapotranspiration, and $\Delta$ S = change in water content in storage (both surface and subsurface).

The water-balance calculations can be performed using point measurements of the water-balance components. The water-balance equation components can also be estimated over some two-dimensional domain, such as the area over the repository, using an interpolation scheme such as kriging. The water balance then needs to be extended or integrated temporally. The equation can be solved at different times of the year for different periods (i.e., when R and P equal 0) to better evaluate the seasonal distribution of net infiltration. This type of analysis will help determine if net infiltration is a seasonal event (i.e., long-duration cold fronts and winter snow melt), or if it follows more catastrophic events (i.e., major precipitation and runoff events, such as thunderstorms).

It should be noted that the errors in measured values of each component may be larger than net infiltration for a period of time. However, the water-balance approach is a good technique for sensitivity analyses and conditional simulation for long-term modeling exercises.

3.2.3.4.2 Measurements, models and prototype development

In analyzing water balance, an integrated approach is needed. This approach requires detailed, long-term measurements as well as statistical and deterministic models. The following section discusses the integration of the measurements, models, and prototype development required to acheive the water-balance analysis.

3.2.3.4.2.1 Precipitation

The areal or spatial distribution of natural precipitation will be determined by a careful analysis of precipitation data, collected by a network of tipping-bucket precipitation gages located throughout the designated catchment areas (see Study 8.3.1.2.1.1). The precipitation record will be analyzed to identify individual "storm" events. Total precipitation, maximum precipitation rates, and storm duration will be compiled, mapped, and analyzed using a Geographic Information System (GIS).

A representative dataset of an average storm event, or a specific individual storm event, within a specific time period (i.e., season, month, or 24-hour period), will be analyzed using geostatistical and classical-statistical techniques. The spatial variability of total precipitation, precipitation rates, and precipitation duration will be defined and modeled for a "representative" storm event

within a designated time period. Conditional simulations and the geostatistical models will be used to develop two-dimensional simulations of measured precipitation events, which can then be used in water-balance models.

The analysis of the precipitation record (including historical records) will also involve the use of geostatistics, classical statistics, and time-series analysis, to define the temporal and spatial distribution and variability of individual storm events. The probability of specified precipitation intensities at points of measurement, within a given time interval and for a given sequence of precipitation events, will be determined. Temporal variability, and the range of temporal correlation, for different types of events (frontal precipitation, convective precipitation, or a combination), will be modeled stochastically (e.g., by time-series analysis), and integrated into the two-dimensional models of spatial variability. Orographic influences will be modeled using multivariate geostatistics and the correlation between precipitation and elevation, while other influences, such as storm track and velocity, can be modeled using deterministic components.

Preliminary analysis of historical precipitation data (French, 1985) has provided a quantitative estimate of precipitation on and around Yucca Mountain (Figure 3.2-9). Geostatistical analysis of elevation and average annual precipitation used to cokrig precipitation (Hevesi and others, 1989a,b) for the Amargosa Watershed (Figure 3.2-9), in which Yucca Mountain is centrally located. Yucca Mountain receives approximately 150 mm of precipitation at the south end and over 200 mm in the north. The increase to the north is topographically induced (Hevesi and others, 1989a,b). An advantage of using geostatistical analyses is that the uncertainty of the interpolated parameter is also estimated.

Figure 3.2-10 represents the cokriged variances for the contours in Figure 3.2-9. The lowest variances are the small circles and are located at measurement points. The variance at Yucca Mountain (approximately 700 $mm^2$) means that an estimate of precipitation (175 mm/yr) has a 95% confidence interval of approximately 50 mm/yr. The high uncertainty in this value has led to the development of an intense network of precipitation stations which are discussed in Study 8.3.1.2.1.1. The highest variances are to the south, west and north, which indicates areas that require precipitation stations. To describe precipitation with any degree of accuracy for the Amargosa watershed, precipitation stations must be installed in those areas. The same technique of variance analysis will be used in the smaller scale of Yucca Mountain.

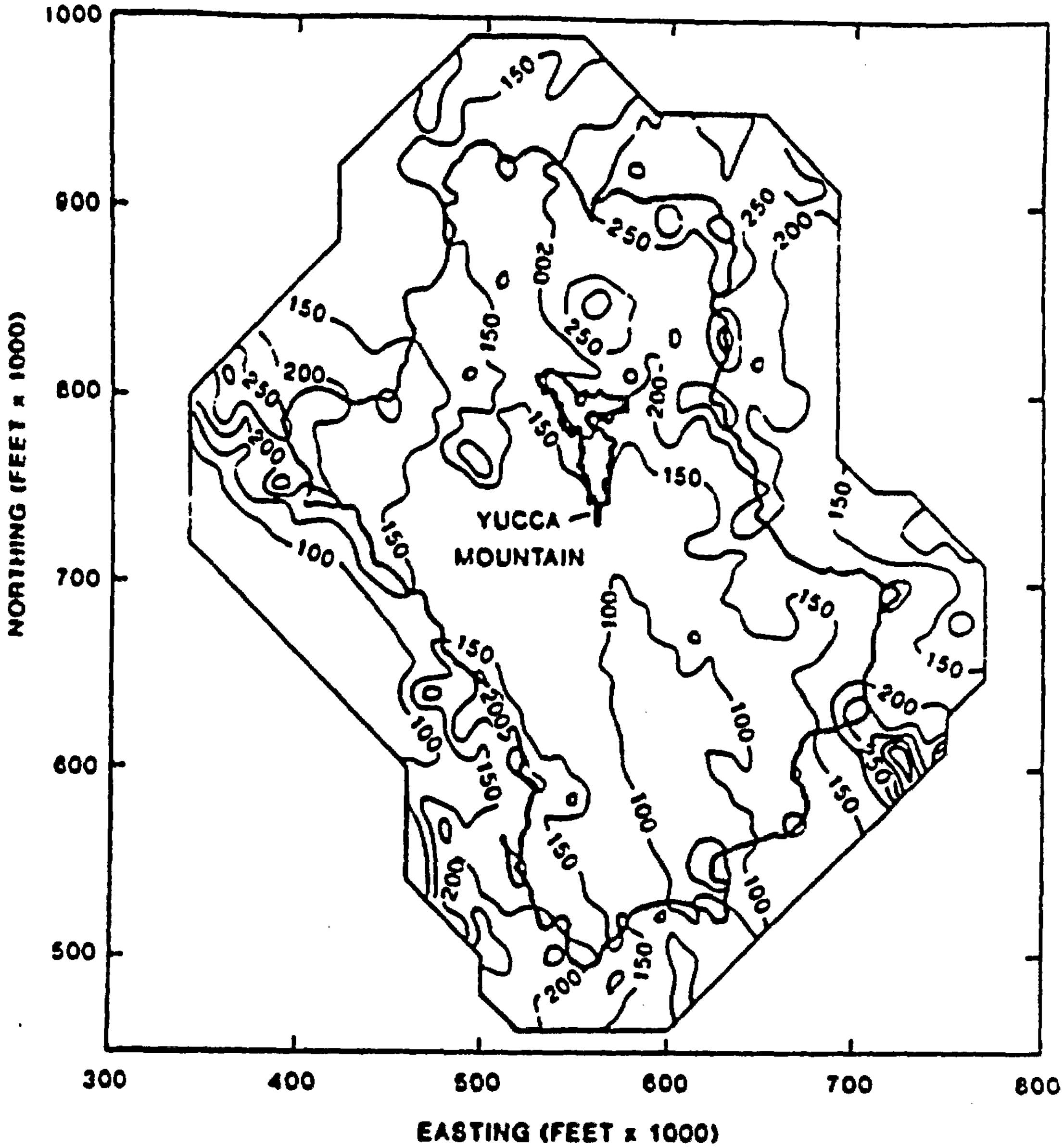


Figure 3.2-9 Map showing cokriged estimates of average annual precipitation using elevation, for the Amargosa watershed. Yucca Mountain is the centrally located outline

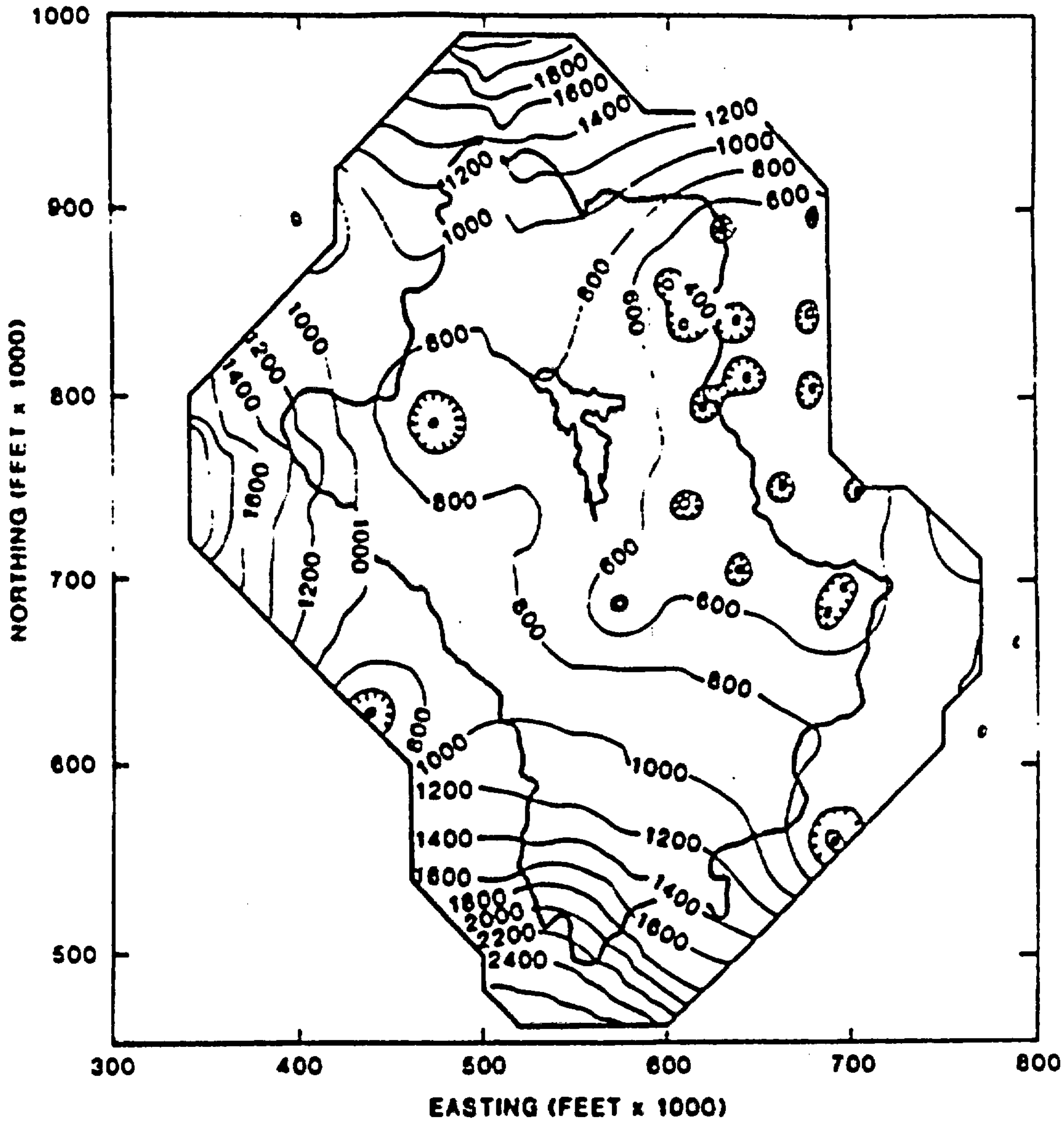


Figure 3.2-10. Map showing cokriged variances ($mm^2$) estimated average annual precipitation for the Amargosa watershed. Yucca Mountain is the centrally located outline. The low variance points represent locations of precipition stations.

3.2.3.4.2.2 Surface runoff and change in storage

Runoff can be measured directly in stream channels (drainages) at several locations within the catchment area, the total catchment area being defined by the measurement taken at the lowest elevation. Runoff measurements are subject to much larger errors than precipitation measurements because of the limitations of stream gaging methods and the constant changes in the water fraction of runoff during a flow event (Study 8.3.1.2.1.2, Characterization of runoff and streamflow).

It might be noted that the runoff component is also needed to determine channel-transmission losses and predict erosion rates. To measure runoff, surface-water gaging stations will be established and instrumented to measure discharge and sediment load in channels draining geohydrologic-surficial units of interest. When possible, small portable flumes will be used to directly measure the runoff from slopes. In addition, a number of small swales near the crest of Yucca Mountain will be instrumented to measure the relative contribution of overland flow and interflow to runoff in first-order streams.

The Yucca Mountain drainage network includes the area of the proposed central repository block and contiguous areas. This network will be analyzed in order to complement the characterization of hydrologic properties of surficial materials described in Section 3.1.3.1.

The analysis of similar watersheds is important in relating measurements and models in one watershed with another (Chow and others, 1988). The total drainage network includes 482 streams containing 320 km of drainage channels in an area of 120 km². Four major subdrainage areas make up the Yucca Mountain drainage network (Figure 3.1-4). These are Yucca Wash, Fran Ridge, Busted Butte, and Solitario Canyon. Table 3.2-3 lists the drainage network characteristics for the subdrainage areas. This preliminary list includes stream order, stream lengths, and drainage density. Additional geomorphic and topographic parameters will be measured and related to runoff and streamflow data. These will include length properties of the drainage network, shape or area of the drainage basin, relief aspects, and physical characteristics. The change in the storage term is addressed in Section 3.2.3.1.3 (utilizing neutron-moisture logging).

Table 3.2-3. Draingage network characteristics for sub-drainage areas.

| SUBDRAINAGE | STREAM NUMBERS Total number of streams of each order | | | | | STREAM LENGTHS Mean length of stream segments of each order: (km) | | | | DRAINAGE DENSITY | | Σl/A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n1 | n2 | n3 | n4 | n5 | 11 | 12 | 13 | 14 | Total area of each drainage area (Sq. km) (A) | Total stream lengths Σl (km) | |
| Yucca Wash | 139 | 40 | 8 | 1 | 0 | 0.42 | 0.61 | 2.83 | 0.002 | 43.2 | 105.8 | 2.45 |
| Fran Ridge | 103 | 31 | 9 | 3 | 1 | 0.61 | 1.16 | 0.90 | 3.14 | 35.9 | 116.8 | 3.26 |
| Busted Butte | 62 | 18 | 7 | 2 | 1 | 0.48 | 0.95 | 0.84 | 1.18 | 16.7 | 57.6 | 3.45 |
| Solitario | 42 | 12 | 2 | 1 | 0 | 0.62 | 0.86 | 0.78 | 5.38 | 23.3 | 43.4 | 1.86 |

Assuming no changes in storage, measurements of total runoff, together with the calculated total precipitation and total evapotranspiration over the catchment area, can be used in the mass-balance calculations to estimate net infiltration.

### 3.2.3.4.2.3 Evapotranspiration

Evapotranspiration in arid and semi-arid regions is perhaps one of the most difficult measurements to make (de Bruin, 1988). A combination of measurements and models will be required to adequately estimate evapotranspiration. A series of prototype methods are currently being developed to determine their suitability under different topographic conditions. Modeling will be used extensively as a measurement confirmation and a spatial and temporal integration technique. The focus of the measurements and modeling will be based on the characterization of the energy balance:

$$Q^* - G - S - LE = 0$$

where $Q^*$ is net radiation, G is soil heat flux, S is sensible heat flux, and LE is latent heat flux (L is the latent heat of vaporization of water and E is the quantity of water evaporated or condensed on the surface). The intent is not to solve the energy balance for the component parts but to use the energy balance framework to analyze the most critical parts and concentrate measurement efforts on those parameters which cannot be adequately predicted using models (which are described later in this section).

The models will help to focus the need for long-term measurements of environmental parameters by identifying those measurements which are most critical for determination of evapotranspiration. Although the focus of the following section is on evapotranspiration, the section also will discuss an approach to measuring and modeling the energy balance.

3.2.3.4.2.3.1 Latent and sensible heat flux

There are several techniques currently under evaluation to measure latent heat flux (see Study 8.3.1.2.1.1). These include the Bowen ratio, eddy correlation, fast-response psychrometers, lysimeters, and class A evaporation pans (see Brutsaert, 1982, for discussion on these techniques). The Bowen ratio (the ratio of sensible heat to latent heat) is the only indirect measurement of evapotranspiration, as it uses an energy-balance calculation to solve for LE and therefore requires measurements of Q* and G. The other four techniques are direct measurements but are also checked against the energy balance to evaluate energy-balance closure. Both eddy correlation and the fast-response psychrometer technique can be used to calculate Bowen ratios and allow intercomparison between techniques. The large spatial variability of precipitation, and therefore evaporation, make the use of these three techniques more difficult. They require an adequate fetch over which evaporation represents an average value. If large-scale advection is present, then modification of the techniques are required (de Bruin, 1988). Another problem is the mountainous terrain which makes the long fetch requirement more difficult. It may be possible to place the sensors in a variety of topographic settings which allow for measurement of evaporation in up-canyon or down-canyon wind.

Estimates of evapotranspiration using meteorological data and modeling will be evaluated and compared to direct measurement of evapotranspiration and soil water loss when drainage is zero. A number of simplifications of the energy-balance technique have been used in order to decrease the quantity and intensity of measurements required. The Penman equation (Penman, 1948) is commonly used in situations where detailed environmental data are available. Simplifications introduced to model the aerodynamic parts of the equation make the equation useful only for calculation of potential evapotranspiration. Furthermore, the equation requires calibration (fitting the parameters to field data). The Penman-Monteith combination equation (Monteith, 1964) allows for calculation of actual evapotranspiration but requires detailed knowledge about the resistance to water flow at the evaporating surface. Priestley and Taylor (1972) suggested a modification of the Penman equation for potential evapotranspiration which requires less extensive measurements. Flint and Childs (1987a) developed a calibration technique that uses the Priestley-Taylor framework to calculate actual evapotranspiration on a daily basis. This technique

relates the reduction in evapotranspiration to a reduction in soil water content, rather than an increase in plant resistance. Considering the sparsity of vegetation and dominance of direct soil surface evaporation, this technique may work quite well. This technique will be evaluated for its applicability to Yucca Mountain. As the evaluation progresses, other models may also be derived to help better estimate evapotranspiration.

3.2.3.4.2.3.2 Net radiation

The measurement of net radiation is often assumed to be simple and is given minor consideration in energy-balance studies. Although there are many net radiometers that can be purchased and installed in the field, determining the proper calibration is difficult. A group of net radiometers were compared as part of this study (Flint and Davies, 1988) and found to have considerable deviation from each other. A method for calibrating net radiometers for desert terrain is currently being developed by using upward- and downward-looking precision-spectral pyranometers (shortwave) and precision-infrared radiometers (longwave). When combined, the radiation balance yields net radiation. This technique allows for calibrating a variety of radiation sensors as well as models of component parts (Flint and Davies, 1988).

Radiation modeling consists of modeling the component parts of net radiation (i.e., incoming and outgoing long- and shortwave radiation). The major component of net radiation is solar radiation. Adequate methods are available for long-term radiation measurements but these measurements are too expensive to be routinely made on a large number of sites. Flint and Childs (1987b) developed a solar radiation model that properly accounts for sloping, mountainous terrain where surrounding ridges can block significant amounts of direct-beam and sky-diffuse radiation and increase the amount of ground-reflected radiation. This model, when calibrated for Yucca Mountain, and combined with measurements of albedo, can easily calculate the shortwave radiation balance (Flint and others, 1987).

Longwave radiation is emitted by the sky and the soil. Measurements or models of soil-surface temperature can be used with the Stefan-Boltzman equation to calculate emitted longwave radiation. There are a variety of equations available to calculate longwave radiation emitted from the sky (Hatfield and others, 1983). The equations will be calibrated and evaluated for the Yucca Mountain region. The equation inputs include air temperature and relative humidity, both standard

measurements of the USGS microclimate weather station (Section 3.2.3.4.2.3.4).

3.2.3.4.2.3.3 Soil heat flux

The thermal properties of major importance to heat flow processes in soil are heat capacity and thermal conductivity. Whole-soil heat capacity, (heat storage for unit-temperature change), is calculated as the sum of the heat capacities of the individual soil constituents. Water is the soil constituent with the largest specific heat and is therefore an important component of whole-soil heat capacity. Thermal conductivity, (rate of heat transfer per unit temperature gradient), is determined by both component thermal conductivities and their arrangement in the soil matrix. Thermal conductivity can be calculated from equations relating bulk-soil properties of water content, bulk density, and porosity as well as the thermal conductivity of individual soil particles and their shape and orientation in the soil (de Vries, 1963).

Estimates of thermal conductivity at Yucca Mountain are particularly difficult because of soil heterogeneity due to rock fragments and exposed bedrock. Soil density and water content vary considerably with depth, largely due to the presence or absence of rock fragments. Rock fragments influence heat transfer in wet soils by reducing total porosity and may also restrict drainage to maintain increased surface-water contents after precipitation events (Flint and Childs, 1984a). In wet soils, the presence of rock fragments can either increase or decrease heat capacity but thermal conductivity is usually increased. In dry soils, where reduction in total porosity has little effect on water content, both heat capacity and thermal conductivity are increased.

Soil thermal diffusivity, the ratio of thermal conductivity to heat capacity, is used in many numerical methods to predict soil temperature and soil-heat flow (Hanks and others, 1971; Horton and others, 1983). Often, however, the thermal diffusivity is not known and must be estimated. Although a number of measurement techniques have been used, many researchers currently use techniques involving an inverse solution of the heat flow equation for homogeneous soils using numerical methods (Firdaouss and others, 1983; Horton and others, 1983). Flint and Childs (1987c) have further developed this technique for heterogeneous, skeletal soils. This technique can be combined with point measurements of soil-temperature profiles to estimate soil-heat flow for large areas. Measurements of soil-surface temperature,

(from longwave radiation measurements) and one subsurface measurement (a lower boundary condition) would be required to estimate soil-heat flow. These measurements are fairly easy to obtain and will be a component part of the meteorology network described in Study 8.3.1.2.1.1. Other techniques for measuring soil-heat flow, such as heat-flux plates (Fuchs and Tanner, 1968), and the calorimetric method (Campbell, 1977), will be evaluated as part of this study.

3.2.3.4.2.3.4 Micrometeorology

Five weather stations have been established on and around Yucca Mountain. A weather station consists of instruments to measure solar radiation, air temperature, relative humidity, wind speed, wind direction and precipitation (one station currently measures barometric pressure). The measurements are taken every 10 seconds and recorded as averages every 15 minutes. The precipitation measurement is recorded to the nearest 10 seconds at a resolution of 0.1 mm. These data will be used as input to modeling and analysis of spatial variability. These data will also be supported by micrometeorological measurements made at eddy-correlation and Bowen-ratio sites, as well as historical data collected in and around southern Nevada by the U.S. Weather Service (see Study 8.3.1.2.1.1). Sites selected as part of the precipitation network will also be instrumented to some extent. These measurements will include precipitation, air temperature, and soil temperature with the possible addition of fast-response psychrometers, wind speed and relative humidity. All of these parameters can be related to evapotranspiration through the use of models (Campbell, 1977).

3.2.3.4.3 Site characterization

When sensitivity analyses and prototype evapotranspiration measurements are concluded, the site-characterization work will begin. Technical procedures will be written to cover the scope, accuracy and equipment required for each component of the water balance and the radiation balance. Since the total error of the water balance technique is expected to be greater than net infiltration, this technique will help to identify regions requiring more intense studies (i.e., areas of high rainfall or high evapotranspiration). Models will also be developed for the purpose of handling spatial variability and for running conditional simulations of the different balance components. The water-balance/energy-balance approach will be modified as necessary when more site-specific data are available.

3.2.3.5 Geostatistical analysis of the spatial variability of natural-infiltration parameters

In trying to characterize hydrologic-surficial units at Yucca Mountain, it is impossible to adequately sample and test the entire region to obtain a deterministic evaluation of surficial physical and hydrologic parameters. Therefore, geostatistical methods will be used to estimate parameters from the available data base. In addition, they will be used to determine locations for new boreholes based on areas of high variance. Autocorrelation functions, semivariograms, and cross-semivariograms will be used to develop appropriate models for spatial structure for each hydrologic parameter. Kriging, and co-kriging (Journel and Huijbregts, 1978) will be used to estimate hydrologic properties between measuring points based on spatial structure and to determine the uncertainty of the estimates. Estimates obtained from geostatistical techniques will be combined with all available laboratory and field data to delineate hydrologic-surficial units at Yucca Mountain and to obtain input needed for larger unsaturated-zone models.

3.2.3.6 Methods summary

The parameters to be determined by the tests described above are summarized in Table 3.2-4. Also listed are the selected and alternate methods for determining the parameters and the current estimate of the parameter-value range. The alternate methods will be used if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, only the most common methods are included in the table. The selected methods in Table 3.2-4 were chosen primarily on the basis of accuracy, precision, duration of methods, expected range, and lack of interference with other tests and analyses.

The USGS investigators have selected methods which they believe are suitable to provide accurate data within the expected range of the site parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.2.4 Technical procedures

The USGS quality-assurance program plan for the YMP (USGS, 1986) requires documentation of technical procedures for all technical activities that require quality assurance.

Table 3.2-5 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a USGS procedure number and an effective date. Procedures that are not identified with an effective date will be completed and available 30 days (for standard procedures) or 60 days (for non-standard procedures) before the associated testing is started; these procedures are also identified with a "TBD" (To Be Continued) technical procedure number. Some of the listed technical procedures are primarily outside the objectives of the subject activity, but are included for general information and ease of cross referencing. Approved technical

Table 3.2-4. Summary of tests and methods for natural infiltration activity (SCP 8.3.1.2.2.1.2)
[Dashes (--) indicate information is not available or not applicable.]

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| | Neutron-access borehole monitoring and analysis | |
| Measure water-content profiles by neutron-moisture logging (selected) | Water-content profiles | 1 to 60% $cm^3/cm^3$ |
| Measure water-content profiles by other geophysical-logging methods (e.g., gamma-gamma, neutron porosity) (selected) | " | 1 to 60% |
| Measure water-content profiles by collecting and analyzing core (alternate) | " | " |
| Calculate net-infiltration rates from water-content profiles (selected) | Infiltration rate, net | 0 to 1 m/hour |
| Model net-infiltration rates from physical properties of surface materials (e.g., texture, porosity) (alternate) | " | Less than 1 m/hour |
| Calculate surface-infiltration rates from water-content profiles (selected) | Infiltration rate, surface | 0 to 1m/hour |
| Model surface-infiltration rates from physical properties of surface materials (e.g., texture, porosity) (alternate) | " | Less than 1 m/hour |
| Determine rainfall-runoff relations by analyzing water-content profiles, rainfall, and rainfall data (selected) | Rainfall-runoff-infiltration relations | Variable depending on surface-infiltration rates. Estimated infiltration rates: maximum 1 m/hour, minimum .01m/hour |

Table 3.2-4. Summary of tests and methods for natural infiltration activity (SCP 8.3.1.2.2.1.2)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| | *Neutron-access borehole monitoring and analysis--Continued* | |
| Determine rainfall-runoff relations by modeling (calculating) from physical and hydrologic properties of surficial materials (alternate) | Rainfall-runoff-infiltration relations | Variable depending on surface-infiltration rates. Estimated infiltration rates: maximum 1 m/hour, minimum .01m/hour |
| Determine water-potential profiles by tensiometer-transducer and heat-dissipation probe methods (selected) | Water-potential profiles | 0 to -300 kPa (current lower limit of heat-dissipation probes) |
| Calculate water-potential profiles from water-content profiles and moisture-retention relations (alternate) | " | " |
| Determine water-potential profiles by moisture-block method (alternate) | " | 0 to -100 kPa for fiberglass or nylon blocks. 0 to -500 kPa with gypsum blocks |
| Determine water-potential profiles by thermocouple psychrometers (alternate) | " | 0 to -7,000 kPa |
| | *Monitoring of natural infiltration in artificial--infiltration control-plot studies* | |
| Measure water-content profiles beneath artificial-infiltration control plots by crosshole gamma-gamma logging (selected) | Water-content profiles | 0 to 70% |
| Measure water-content profiles beneath artificial-infiltration control plots by collecting and analyzing core (alternate) | " | 1 to 60% |

Table 3.2-6. Summary of tests and methods for natural infiltration activity (SCP 8.3.1.2.2.1.2)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Monitoring of natural infiltration in artificial-infiltration control-plot studies--Continued** | | |
| Measure water-content profiles beneath artificial-infiltration control plots by other geophysical logging methods (selected) | Water-content profiles | 0 to 70% |
| Determine water-potential profiles by tensiometer-transducer and heat-dissipation probe methods (selected) | Water-potential profiles | 0 to -300 kPa (current lower limit of heat-dissipation probes) |
| Calculate water-potential profiles from water-content profiles and moisture-retention relations (alternate) | " | -- |
| Determine water-potential profiles by moisture-block methods (alternate) | " | 0 to -100 kPa for fiberglass or nylon blocks. 0 to -500 kPa with gypsum blocks |
| Determine water-potential profiles by thermocouple psychrometers (alternate) | " | 0 to -7,000 kPa |
| Calculate net-infiltration rates from water-content profiles (selected) | Infiltration rates, net | 0 to 1 m/hour |
| Model net-infiltration rates from physical properties of surface materials (e.g., texture, porosity) (alternate) | " | Less than 1 m/hour |
| Calculate surface-infiltration rates from water-content profiles (selected) | Infiltration rates, surface | 0 to 1 m/hour |
| Model surface-infiltration rates from physical properties of surface materials (e.g., texture, porosity) (alternate) | " | Less than 1 m/hour |

Table 3.2-4. Summary of tests and methods for natural infiltration activity (SCP 8.3.1.2.2.1.2)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Monitoring of natural infiltration in artificial-infiltration control-plot studies--Continued** | | |
| Determine rainfall- and runoff-infiltration relations by analyzing water-content profiles, runoff, and rainfall data (selected) | Rainfall-runoff-infiltration relations | Variable depending on surface-infiltration rates. Estimated infiltration rates: maximum 1 m/hour, minimum .01 m/hour |
| Determine rainfall-runoff-infiltration relations by modeling (calculating) from [illegible]sical and hydrologic properties of [illegible]cial materials ([illegible]rnate) | " | " |
| **Tritium-profiling studies** | | |
| Tritium-profiling studies to determine flow pathways (selected) | Flow pathways | 0 to 130 m/30 years |
| Use other environmental tracers to determine flow pathways (alternate) | " | " |
| Tritium-profiling studies to determine net infiltration (selected) | Infiltration rates, net | " |
| Calculate net-infiltration rates from physical and hydrologic properties (selected) | " | 0 to 1 m/hour |
| Use other environmental tracers to determine net infiltration (alternate) | " | 0 to 130 m/30 years |

Table 3.2-4. Summary of tests and methods for natural infiltration activity (SCP 8.3.1.2.2.1.2)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Water-budget studies--Continued** | | |
| Measure evapotranspiration by Bowen-ratio method (selected) | Evapotranspiration | 0 to 6 mm/day |
| Measure evapotranspiration using lysimeters (selected) | " | " |
| Measure evapotranspiration using class A evaporation pan (selected) | " | 0 to 10 mm/day |
| Measure evapotranspiration using Eddy correlation techniques (alternate) | " | 0 to 6 mm/day |
| Estimate evapotranspiration using computer models (alternate) | " | " |
| Use the water-budget equation to evaluate the error in all components of evapotranspiration (selected) | " | -- |
| Analyze only individual error in the water budget for evapotranspiration (alternate) | " | -- |
| **Geostatistical analysis of the spatial variability of the natural-infiltration parameters** | | |
| Geostatistical analysis to determine spatial variability of natural-infiltration parameters (selected) | Spatial variability of natural-infiltration parameters | -- |

Table 3.2-5. Technical procedures assignments for natural-infiltration activity (SCP 8.3.1.2.2.1.2)

[Dashes (--) indicate information is not available and to be determined.]

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Neutron-access borehole monitoring and analysis** |
| HP-12 | Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS |
| HP-55 | Hydrologic-laboratory testing of core and drill-cutting samples from unsaturated-zone test holes |
| HP-97 | Measurement of temperature and relative humidity using a Campbell Scientific, Inc. 207 temperature and relative humidity probe |
| HP-84 | Sealing neutron access-hole casings at the ground surface |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |
| HP-95 | Tensiometer calibration |
| HP-96 | Neutron moisture meter calibration (vertical holes) |
| | **Monitoring of natural infiltration in artificial-infiltration, control-plot studies** |
| HP-15 | Method for calibrating heat-dissipation sensors for measuring in-situ matric potential within porous media |
| HP-17 | Method of calibration and testing for operation of pressure transducers for air-permeability studies in the unsaturated zone |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |

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Table 3.2-5. Technical procedures assignments for natural-infiltration activity (SCP 8.3.1.2.2.1.2)--Continued

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Tritium-profiling studies--Continued** |
| TBD | Methods to determine flow paths from tritium profiling |
| TBD | Methods to determine net infiltration from tritium profiling |
| | **Water-budget analysis** |
| HP-97 | Measurement of temperature and relative humidity using a Campbell Scientific, Inc. 207 temperature and relative humidity probe |
| HP-95 | Tensiometer calibration |
| HP-96 | Neutron moisture meter calibration (vertical holes) |
| | **Geostatistical analysis of the spatial variability of the natural-infiltration parameters** |
| TBD | Characterization of spatial variability of natural-infiltration parameters |

procedures not listed may be used during the activity, should that be appropriate, and listed procedures may be revised or replaced with other procedures, as needed.

Applicable quality-assurance procedures are presented in Appendix 7.1.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, and calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

## 3.3 Evaluation of artificial infiltration

### 3.3.1 Objectives

The objective of the artificial-infiltration activity is to characterize water movement in the surficial materials of Yucca Mountain under controlled conditions. Experiments designed to determine the total water flux, flow velocities and flow paths will be performed on the geohydrologic-surficial units under both present day precipitation rates and simulated higher rates corresponding to wetter climatic conditions.

A series of four different types of artificial-infiltration tests are proposed in this activity plan: (1) infiltrometer tests, (2) ponding tests, (3) small-plot rainfall simulation (SPRS) and (4) large-plot rainfall simulation (LPRS). Beginning with infiltrometer tests, each type of test increases in complexity and builds on the results of the previous test.

Three major goals to be achieved in order to meet the main objective are:

(1) To characterize the range and spatial variability of infiltration rates in approximately the upper 0.3 m of surficial material.

(2) To characterize the range and spatial variability of infiltration rates, flow velocities and flow paths in approximately the upper 5 m of surficial material.

(3) To characterize the complex relation between rainfall, runoff, evapotranspiration, changes in storage and infiltration in approximately the upper 5 m of surficial material.

### 3.3.2 Rationale for activity selection

The activity is designed to define the upper flux boundary at Yucca Mountain for present-day and simulated wetter climatic conditions.

The infiltrometer, ponding, and rainfall-simulation tests described in this activity permit the rapid collection of large amounts of water-flux, flow-velocity, and flow-pathway data in a relatively short amount of time compared to obtaining the same data under natural conditions. In addition, artificial-rainfall tests which simulate storms typical of wetter climates should yield valuable infiltration data for each event and each type of surficial material. Under future wetter climatic conditions, the soils and vegetation would certainly be different from that found under present-day conditions, (i.e., the upland soils of Yucca Mountain would have more developed horizons and denser vegetation cover than present day). Unfortunately, infiltration tests on present-day soils which simulate storms typical of wetter climates should yield infiltration rates, flow velocities and hydraulic conductivities which may not represent conditions for more developed soils (Analog recharge studies, 8.3.1.5.2.1.4). Further tests and spatial analysis under

different vegetation types may provide the needed information to determine soil characteristics under possible future conditions.

For infiltration tests done over bedrock or shallow soil and alluvial cover, monitoring the advance of wetting fronts using geophysics and groundwater tracers will provide information on fracture-flow paths in the bedrock. Monitoring conservative-tracer movement will yield data on maximum flow velocities (all water used in the artificial infiltration will be tagged with a tracer). The information obtained from such tests will be useful in developing mathematical models to predict ground-water travel time in the unsaturated zone from the repository to the accessible environment.

### 3.3.3 General approach and summary of tests and analyses

Figure 3.3-1 summarizes the organization of artificial infiltration studies. A descriptive heading for each test and analysis appears in the boxes of the second row. Below each test or analysis are the individual methods that will be used. Figure 3.3-2 summarizes the objectives of the activity, design- and performance-parameter categories which are addressed by the activity, and the site parameters measured. These appear in the boxes in the top left side, top right side, and below the test and analysis boxes, respectively, in Figure 3.3-2.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions in the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among: (1) the site parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The general approach proposed for artificial-infiltration studies is summarized as flow diagrams in Figure 3.3-3a, -3b, and -3c. The approach has been divided into 12 major steps identified by Roman numerals. These flow diagrams detail four major prototype tests, four major site-characterization tests, three modeling activities, and one synthesis activity which is repeated four times. In addition, data to be collected from each site-characterization test and the relation between these data and other activities are shown.

Steps X, XI, and XII will be done in cooperation with the USGS Unsaturated-Zone Modeling Project for Yucca Mountain. Details of these models will not be described in this study plan.

Several of the steps outlined in Figures 3.3-3a, b and c have been completed, or work necessary for their initiation has been performed. A plan to evaluate a number of different infiltrometers has been devised and the infiltrometers constructed or purchased. A selection of one or more infiltrometers that can be used under the conditions present at Yucca Mountain will result from comparison tests. These comparison tests will be conducted as a part of activity I, Prototype infiltrometer tests. Activity IIIa has been completed in connection with the siting

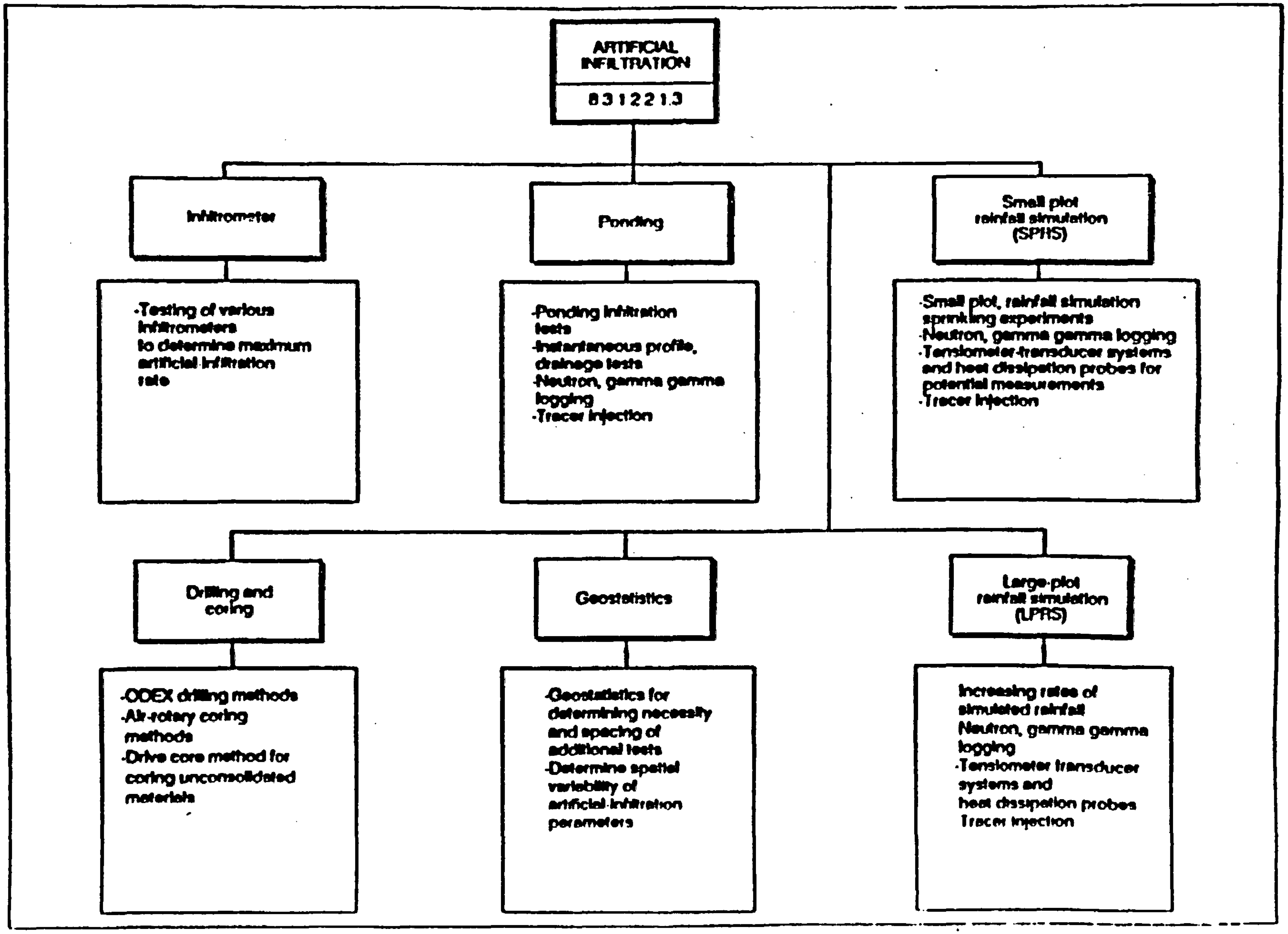


Figure 3.3-1 Logic diagram for artificial infiltration showing tests and methods

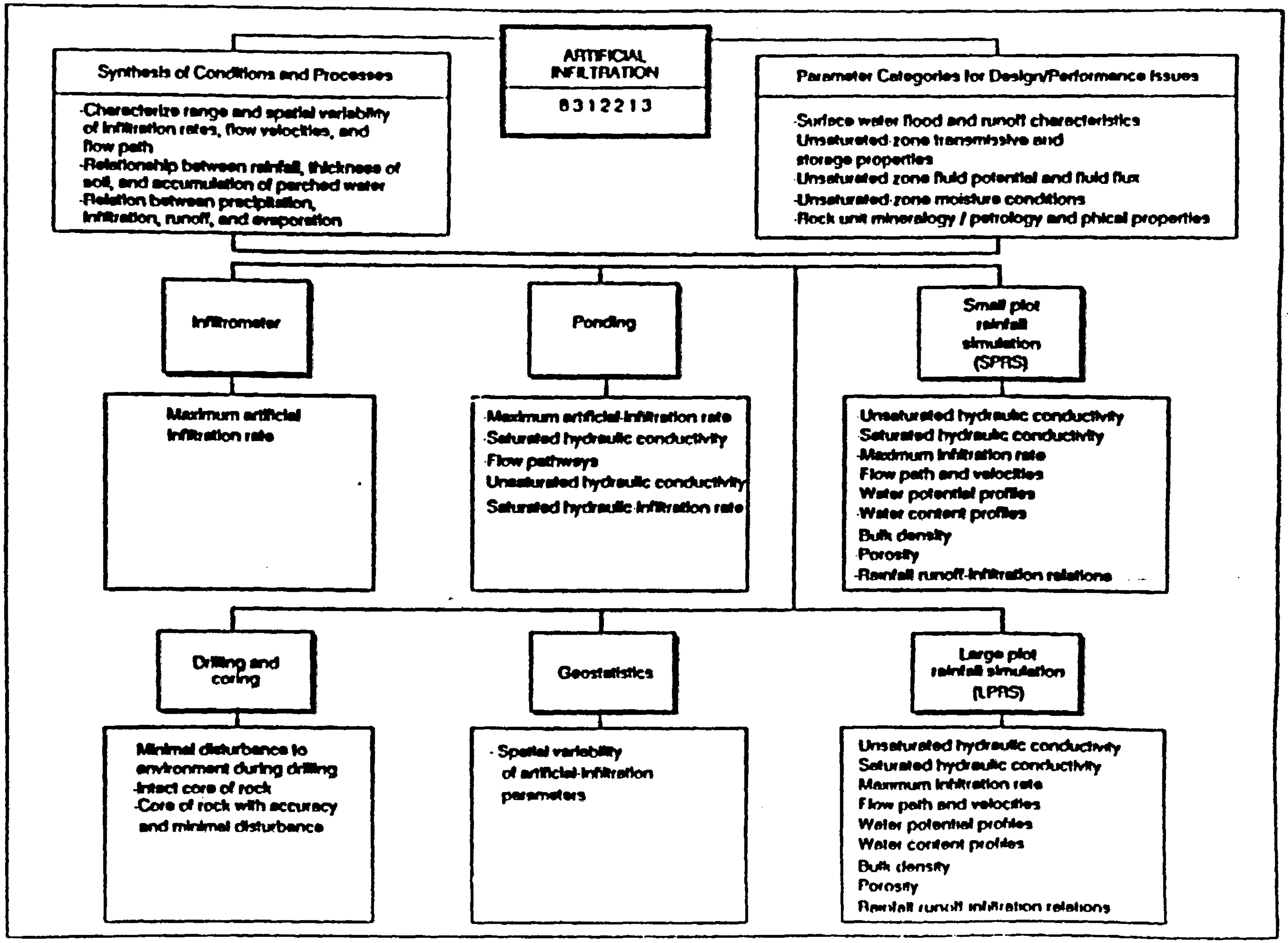


Figure 3.3-2 Logic diagram for artificial infiltration showing tests and site parameters

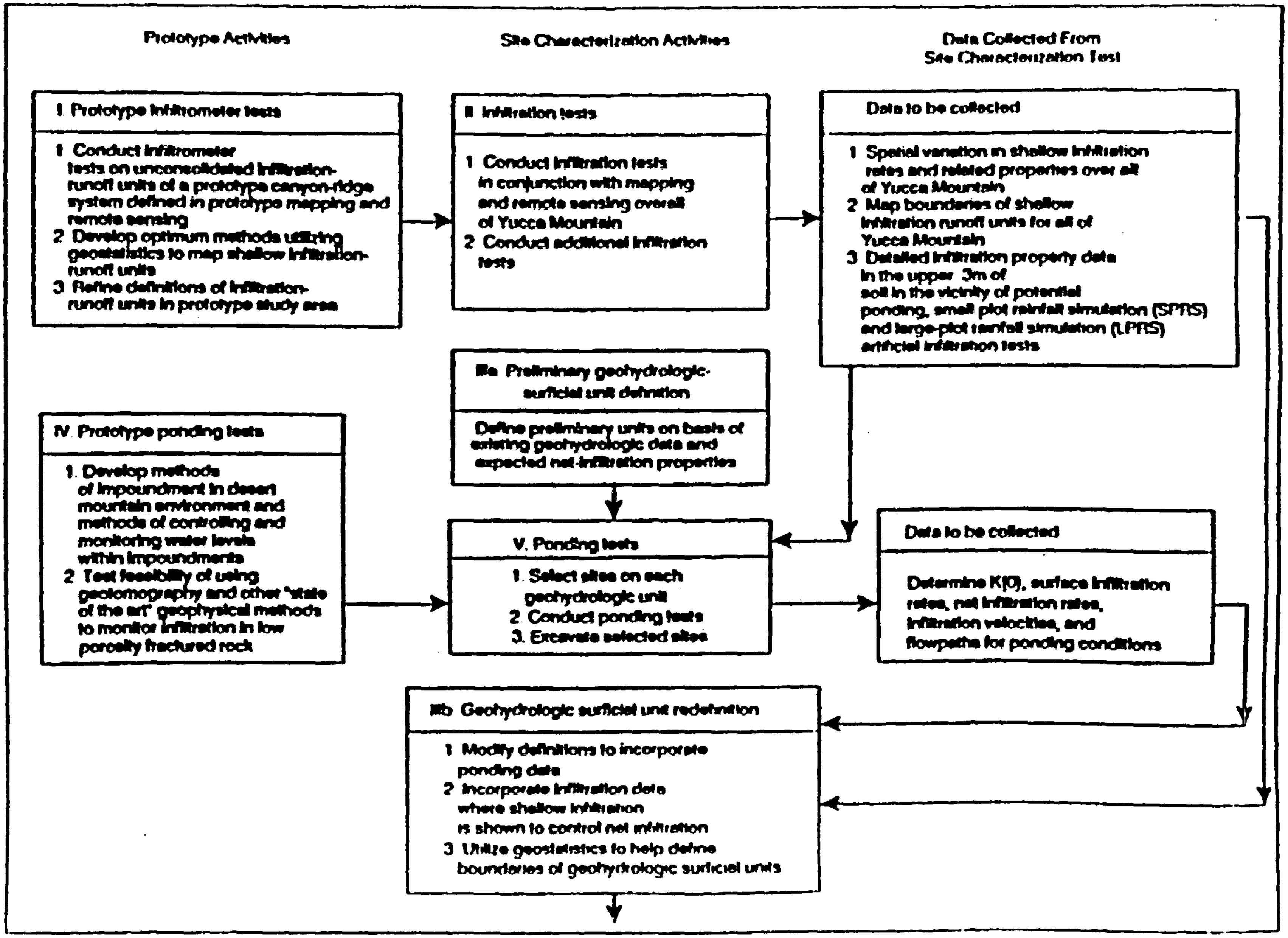


Figure 3.3-3a. Flow diagram for artificial-infiltration tests

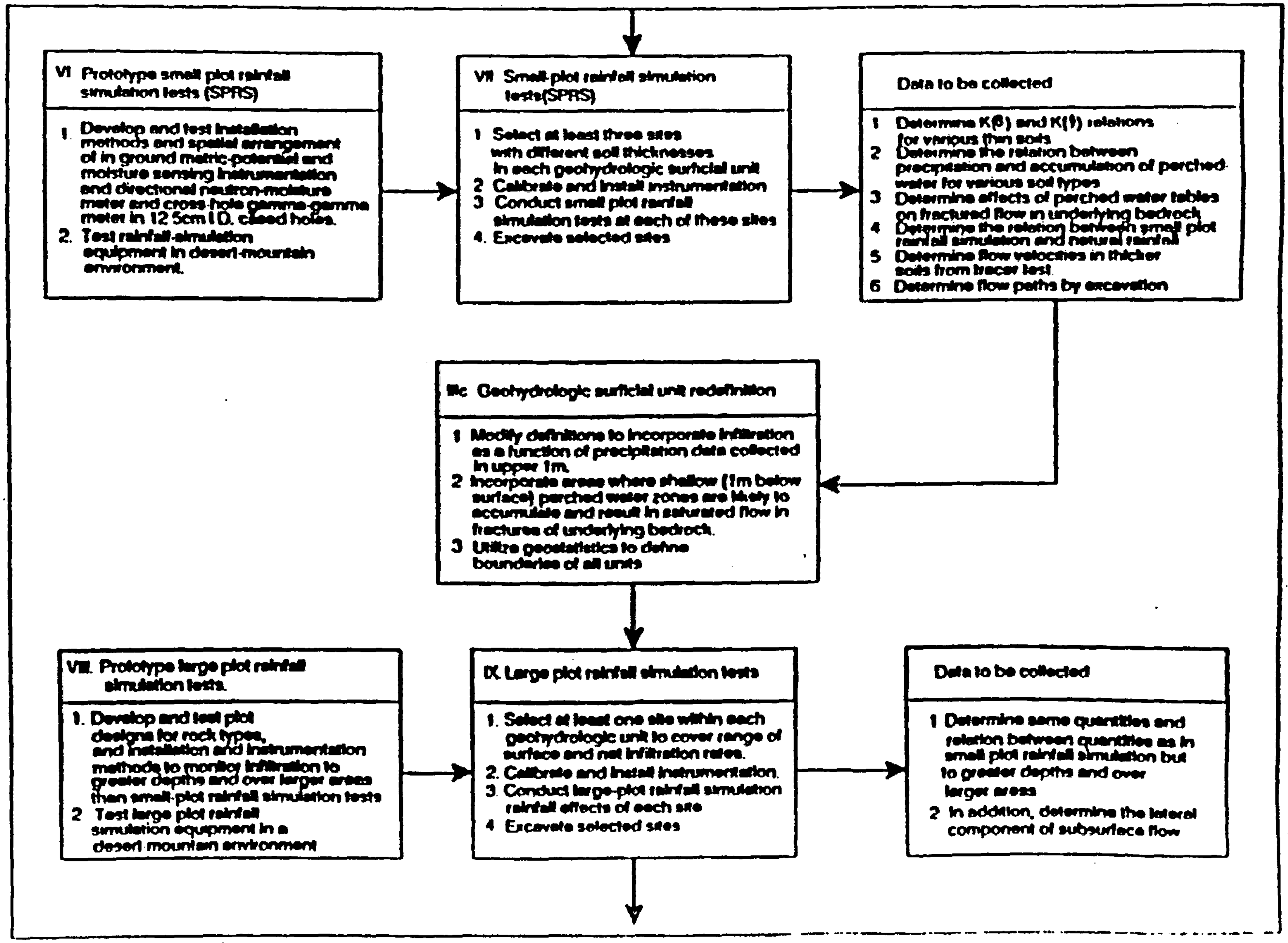


Figure 3.3-3b Flow diagram for artificial-infiltration tests (continued)

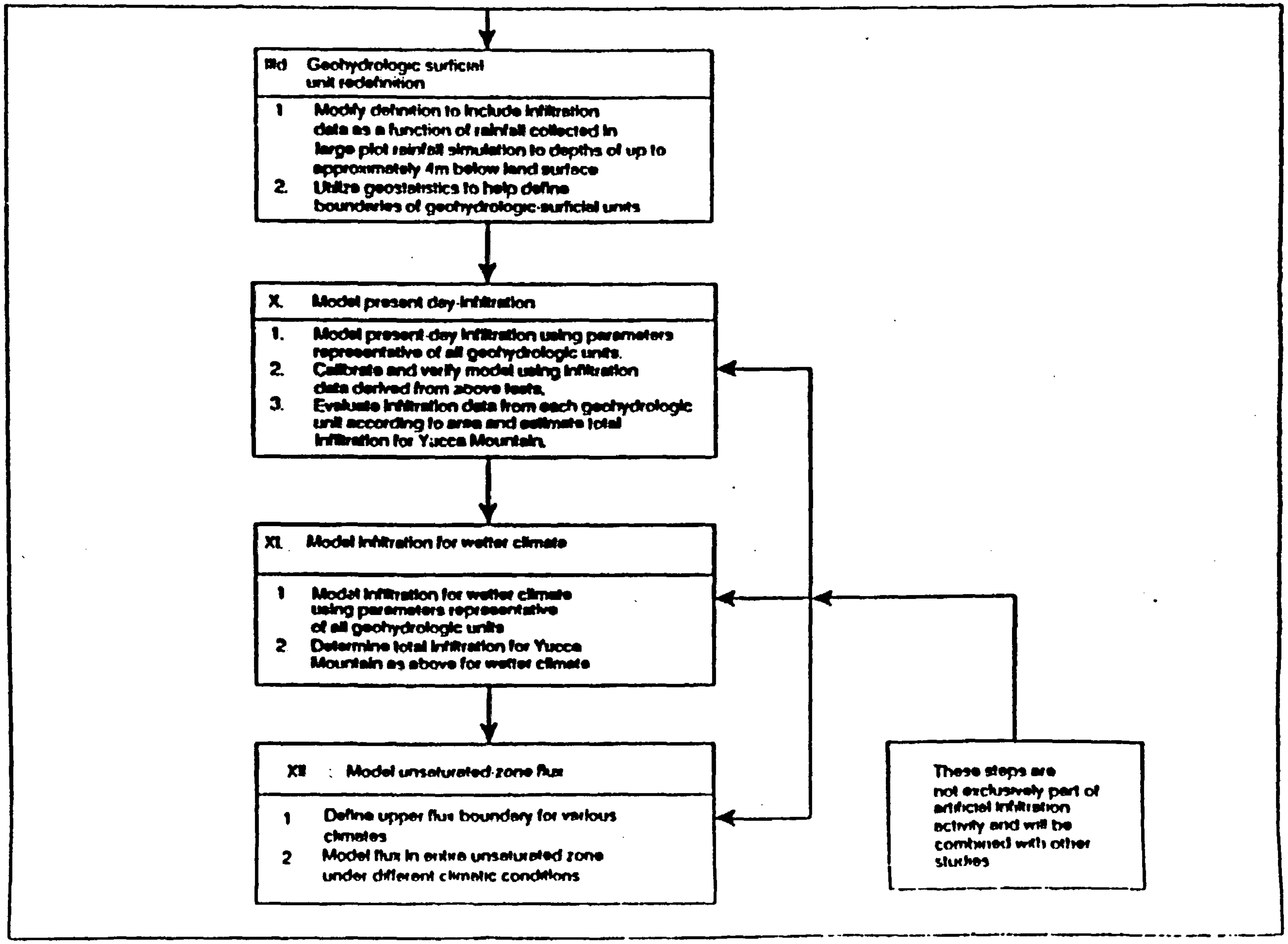


Figure 3.3-3c Flow diagram for artificial-infiltration tests (continued)

of neutron-access boreholes and as a first step in defining the geohydrologic units of the prototype canyon-ridge system (Section 3.1.3.1.1). Results from the canyon-ridge study indicate that more prototype work needs to be completed on surficial-unit classification with respect to hydrologic properties. Activity IV has been partially completed by siting and constructing a prototype impoundment for ponding and artificial-rainfall studies. Development of drilling and casing techniques in unconsolidated sediments for vertical and horizontal instrument installation at the impoundment site is now being performed. In addition to the above activities, many of the instruments to be used in the ponding and artificial-rainfall plots have been tested extensively in the laboratory and under actual field conditions.

The tests involved in the artificial-infiltration activity will be implemented at each of the principal geohydrologic-surficial units at Yucca Mountain. These units include the unconsolidated-surficial materials as well as the bedrock outcrops overlying the repository block. Since all of these principal surficial units are to be tested under this study, the values obtained for the parameters should be representative of Yucca Mountain as a whole. However, to ensure that data obtained are representative, and to quantify the deviation of each parameter value, extensive validation and geostatistical analyses will be performed.

The following sections describe tests and analyses to be conducted as part of the artificial-infiltration tests. Each of the tests described in these sections has been divided into a prototype component and site-characterization component. The prototype component must be successfully completed and evaluated before it can be used for site characterization.

### 3.3.3.1 Infiltrometer measurements

Infiltrometer measurements which characterize surficial-infiltration rates in approximately the top 0.3 m of soil or rock, will be used. The determination of infiltration rates across the surface is important for several reasons. First, the infiltration rate will affect surface ponding for various storm intensities and runoff. Second, the infiltration rate, coupled with the amount of pore space available for flow, will determine the depth to which water will penetrate in a given time period. Third, infiltration rates determined in the field and compared to laboratory measurements on cores will indicate the relative influence of macropores and air entrapment. Fourth, for tests conducted on bedrock surfaces and over very shallow soil cover, infiltration rates into fractures can be measured.

The following is a list of infiltrometers to be used in prototype testing:

Double-ring infiltrometer (Bouwer, 1961)
Shallow borehole permeameter (Reynolds and Elrick, 1985)
Air entry permeameter (Bouwer, 1966)
Surface twin-ring permeameter (Scotter and others, 1982)

Air permeameter (Eijpe and Weber, 1971; Morineau and others. 1965)

Although the theory and assumptions of the various infiltrometers may vary, the overall application is relatively straightforward. Under controlled conditions, a known amount of water is applied to a known surface area under a constant or known head. The volume of water taken in by the soil is measured over known time intervals and is used to calculate infiltration. The infiltration rate is defined as the volume flux of water flowing into the profile per unit of soil surface area.

Infiltration into unsaturated soil is a function of the suction and gravitational gradients. As the wetting front progresses, the average suction gradient decreases until, finally, the upper part of the profile is dominated by the gravitational gradient. Since the gravitational gradient is unity, the infiltration rate approaches the saturated hydraulic conductivity ($K_s$). Because of air entrapment, the field measured hydraulic conductivity, referred to as the transmission zone hydraulic conductivity ($K_t$), can be as much as an order of magnitude lower than the saturated conductivity (Constantz and Herkelrath, 1988).

The initial infiltration rate is higher than $K_t$ due to the larger hydraulic gradient which exists in unsaturated soil. This initial rate is, however, dependent on antecedent moisture content and, when related to the rainfall rate, determines if runoff will occur. Although the final measure of the infiltrometer is $K_t$, a relation can be developed between the initial rate and water content. This relationship can be derived by combining the measured values of $K_t$ with the water release function to calculate unsaturated hydraulic conductivities and potential gradients, which in turn, can be used to estimate infiltration rate at any specific antecedent moisture content (Campbell, 1985).

Infiltrometry will, therefore, be used as the primary method by which the infiltration rates in the upper 0.3 m are determined. Since infiltrometer measurements can be performed easily and rapidly, geostatistical analysis and overlaying of other data bases through a geographic information system can be applied to a small number of measurements to help determine where additional measurements must be taken. This process is then repeated and more tests are done. With this approach, large areas can be characterized efficiently.

As the initial step toward prototype infiltrometer measurements, a field evaluation of several types of infiltrometers will be performed. The infiltrometers selected by this comparative evaluation process will ensure that the proper instrument is used under the special geomorphologic conditions and soil structures encountered on Yucca Mountain.

Evaluation of the infiltrometers will be done by rating each one against an established set of criteria. These criteria were

formulated based on a combination of quantitative and qualitative factors. Specifically, the criteria which have been established are:

(1) Correlation between field measured values and laboratory determination of vertical saturated hydraulic conductivity.

(2) Ability to measure over a representative surface area.

(3) Ability to test soils with different physical characteristics (for example, varying rock-fragment content).

(4) Ability to conform to boundary conditions and assumptions of the method of analysis.

(5) Ability to limit or compensate for temporal conditions.

(6) Ability to characterize only near-surface materials.

(7) Ability to meet project completion requirements.

(8) Portability, durability and ease of use.

The evaluation process may result in the selection of more than one infiltrometer, since no single instrument is expe_ted to be suitable for the broad range of conditions present on Yucca Mountain.

3.3.3.1.1 Prototype studies

Prototype infiltrometer measurements will be done in the prototype canyon-ridge system (tests in the canyon-ridge area are described in Section 3.1.3.1). The preliminary infiltration-runoff map units, as determined through the sampling and mapping activities described in Section 3.1.3.1, will be used as a base for establishing an initial sampling scheme. First, the principal geomorphic units in the canyon-ridge system will be used to stratify the sample. Second, within each layer of this stratification, which will correspond to distinct geomorphic units, a sample grid will be established.

The approach to be used to characterize the spatial variation in shallow infiltration obtained by infiltrometers is summarized in Figure 3.3-4a and -4b. An example of a grid system for a hypothetical surficial unit is presented in Figure 3.3-5. The large-scale surficial-unit grid (A) will consist of approximately 50 sample locations. The small grid is the centrally located plot that is used for the initial survey of approximately 35 close-spaced sampling locations in each surficial unit. These numbers are first approximations, and analysis of the data will allow for revisions of numbers and

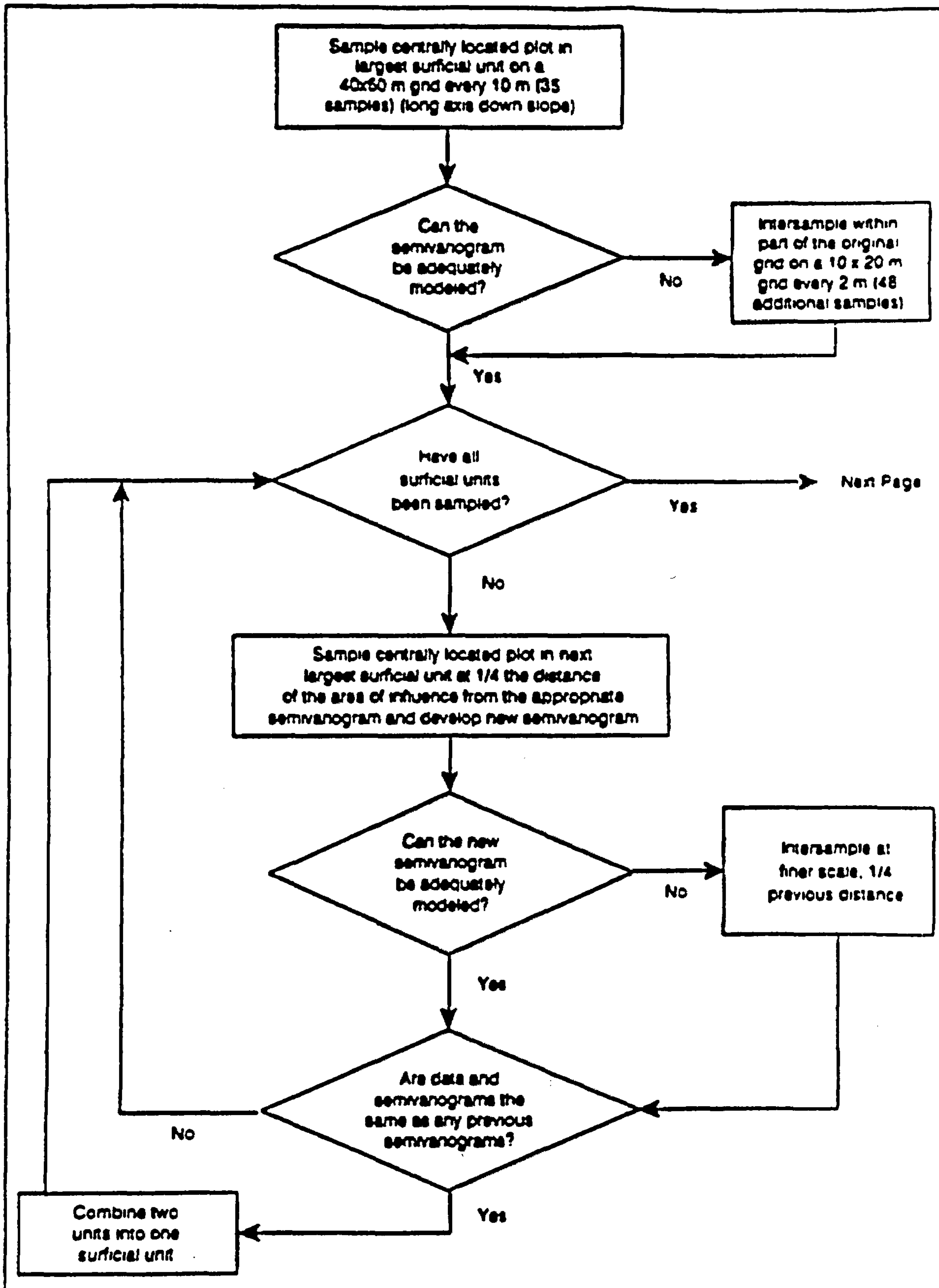


Figure 3.3-4a. Flow diagram for determining spatial variation of infiltration rates determined by infiltrometer tests.

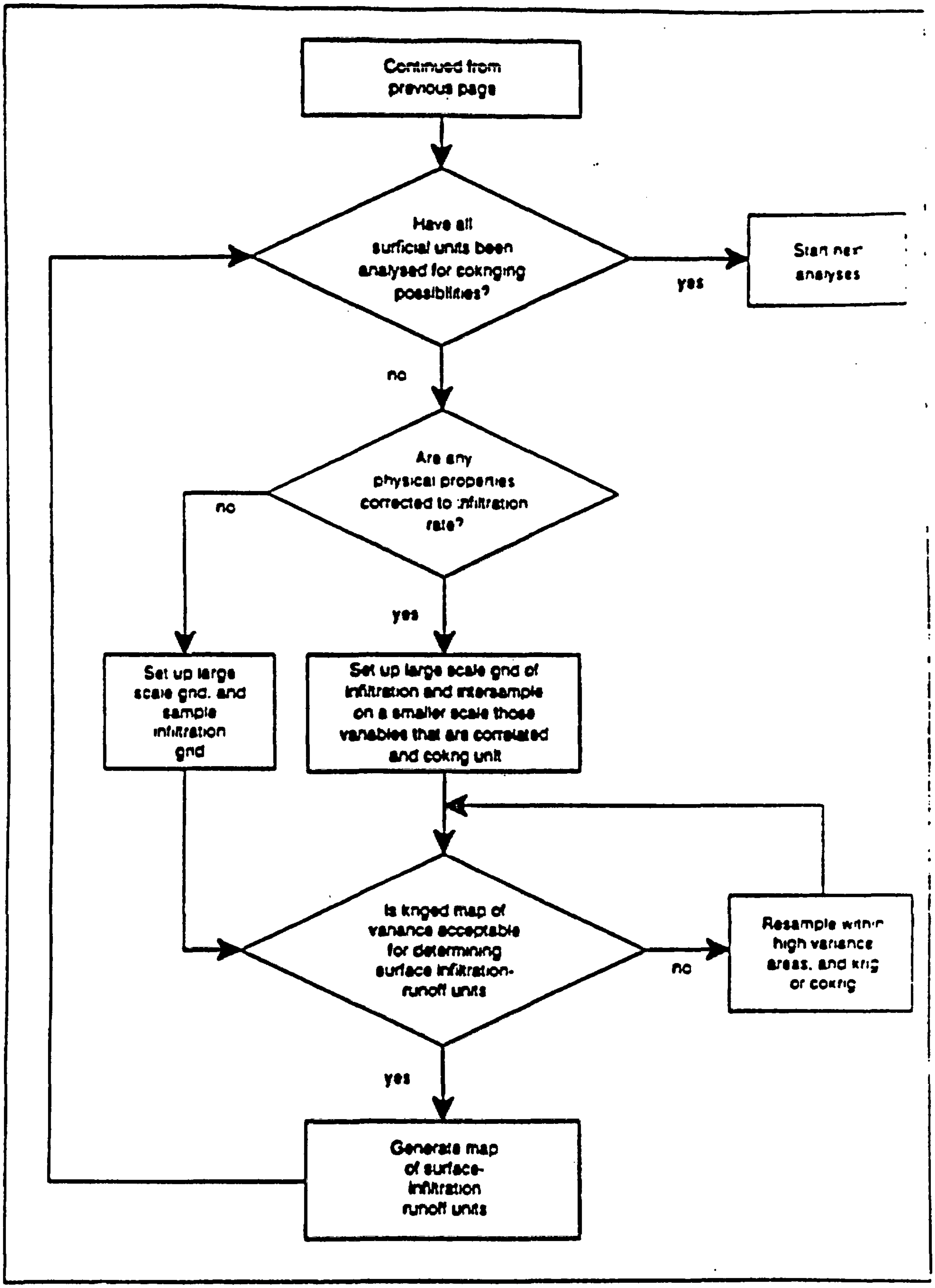


Figure 3.3-4b. Flow diagram for determining spatial variation of infiltration rates determined by infiltrometer tests (continued).

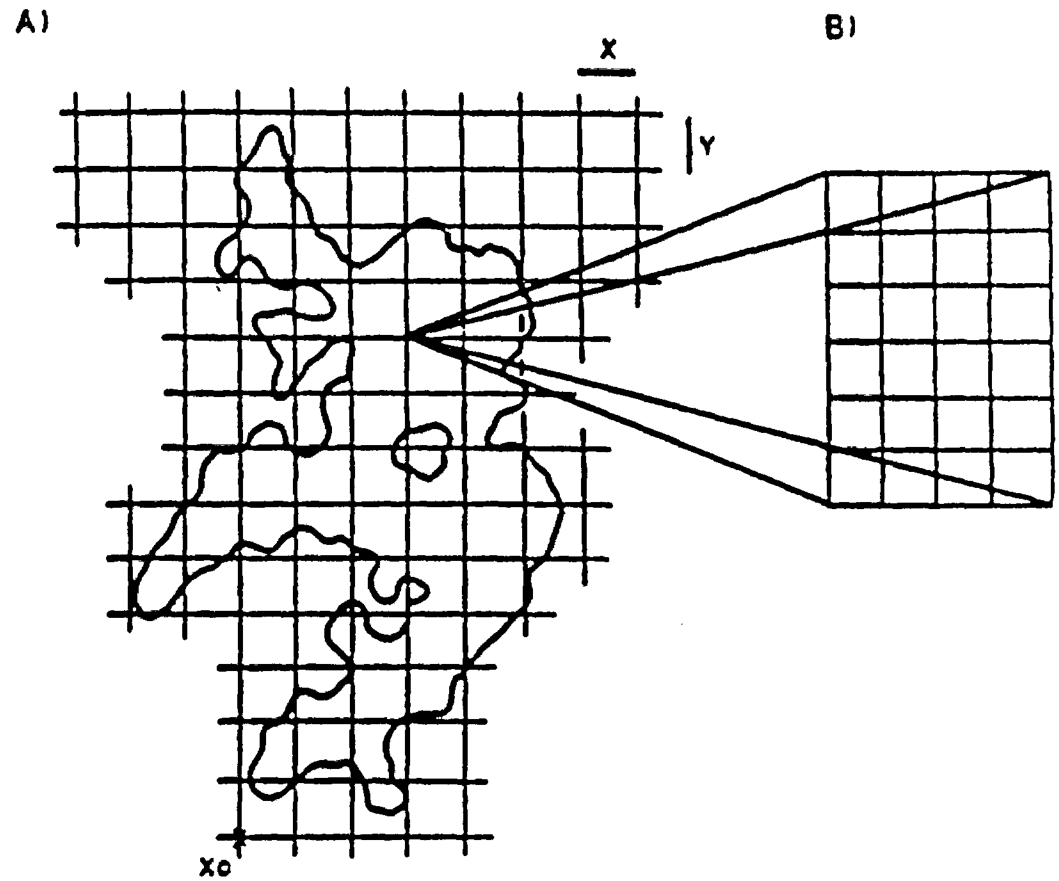


Figure 3.3-5. Map showing proposed grid system for hypothetical surficial unit (A) where Xo is the reference point (0.0). A single, centrally located point will be selected for intensive, closed-spaced (5 x 5 m) sampling (B).

locations. The available regression information will be used to cokrig if possible. If correlations do exist, then intermediate sampling of the correlated variables will be done. If the collection of data for the correlated data is as difficult or more difficult to obtain than the infiltration measurements, then those data will not be collected. A better estimation of the node spacing needed will be based on a site survey and a geostatistical correlation analysis of physical property data acquired by preliminary sampling and mapping activities. As testing progresses, the node spacing may be increased or decreased, depending on a geostatistical analysis of infiltration values obtained.

Initial infiltrometer tests will be performed on each surficial unit. At the end of each test, soil samples will be taken from within the wetted soil volume. Physical and hydrologic properties of these samples will be determined by laboratory tests consisting of bulk density, porosity, particle-size distribution, saturated hydraulic conductivity, water-characteristic curves, and initial water content.

Using the physical and hydraulic data obtained in the laboratory and from the field, regression analysis as well as overlaying and compositing of data bases will be performed to determine which physical properties of the soil most closely correlate with the hydraulic conductivity measured in the field. The objective of this process is to identify an easily measured physical property that can be correlated with the more time consuming measurement of hydraulic conductivity. If such a correlation can be identified, a multivariate-geostatistical analysis can be performed to generate values for points intermediate to the infiltrometer measurements. If no such correlation can be identified, infiltrometers will be used extensively.

Once infiltration-runoff map units are defined, they will then be overlaid on map units defined using techniques described under Section 3.1 (Characterization of surficial materials). Through the overlaying process, the relation between geology, geomorphology and hydrology can be determined. Validation of results through field infiltrometer measurements will be made for each unit mapped.

3.3.3.1.2 Site characterization

If correlation between one or more physical soil properties and infiltration rates can be identified, estimates of infiltration rates for Yucca Mountain will be obtained using numerous measurements of the correlated parameters. If no satisfactory correlation for infiltration rates can be identified, more extensive infiltrometer measurements will be performed.

If, in addition, correlation of infiltration-runoff map units with geology, geomorphology or remotely-sensed spectral response is evident through the process of overlaying and compositing these respective data bases, mapping of infiltration rates over Yucca Mountain will be checked by the overlay process. Any area where correlation is poor will be field checked by making infiltration measurements. Random tests will be included to validate the infiltration estimates obtained using geostatistics.

It is expected that shallow-infiltration rates may also correlate closely with net-infiltration rates determined by prototype ponding tests and natural-infiltration studies. In these cases, the easily made infiltrometer measurements will be substituted for some ponding and rainfall simulation tests.

### 3.3.3.2 Ponding tests

Ponding tests will be used to characterize processes of infiltration, drainage, redistribution, and evapotranspiration. Ponding tests will be performed around some existing neutron-access boreholes as well as some proposed borehole sites. Impoundments will be built to permit the ponding or flooding of surficial units. Instrumentation buried within the profile will be used to monitor the infiltration process down to the depth of interest. After the water supply is shut off at the surface, the drainage, redistribution and evapotranspiration process will be monitored. The total amount of water to be used has not been determined at this time, but will be determined prior to testing (based on prototype testing).

Dye tracer will be added to the water source at two sites, one where there is a substantial depth of alluvium, and another where there is relatively little soil cover over fractured bedrock. The profile at each of these two sites will be excavated after the test and the flow paths mapped. In this way, the relative importance of such flow paths as macropores and fractures can be determined. The dye will be selected after further analysis of available data and results of preliminary infiltration studies.

Further details of this test are yet to be determined, however possibilities for excavation include backhoe, blasting, handtools, shallow boreholes, etc. If possible the profiles will be excavated by layers to determine the lateral extent and specific fractures that transport water. It is expected that there will be a strong correlation between the fractures mapped from the dye tracer study with those determined from the geotomography studies.

#### 3.3.3.2.1 Prototype studies

Two prototype ponding tests will be performed, the first over thick alluvial cover and a second one where a shallow soil covers fractured bedrock. These two types of sites will

represent the end members in the continuum of conditions found on Yucca Mountain.

The first prototype site, over a thick alluvial cover, has been constructed, along with the complementary control plot to monitor natural conditions. Neutron-access tubes have been installed in these plots to a depth of 2 m. Instruments to be used to monitor the physical and hydrologic conditions in the plot are currently undergoing testing and calibration. These instruments include:

(1) Neutron-moisture meter
(2) Transmission gamma water and density instruments
(3) Time Domain Reflectometry instrumentation
(4) Temperature sensors
(5) Thermocouple psychrometers
(6) Tensiometer-transducer system
(7) Heat-dissipation probes
(8) Soil heat-flux sensors
(9) Soil solution samplers
(10) Data retrieval and analysis systems
(11) Water delivery and monitoring systems

In addition, meteorological and micro-meteorological instrumentation for measuring atmospheric parameters used in calculating evapotranspiration is being tested and calibrated. For the special case of monitoring flow in fractured bedrock, the technique of geotomography (Dailey and Ramirez, 1984) will be used to determine flow pathways.

The development of techniques for drilling and casing in unconsolidated surficial materials is currently under way. The objective of this program is to devise methods for installing unsaturated-zone instrumentation in small vertical and horizontal boreholes with the little disturbance to the profile. Currently, no techniques exist to penetrate the types of sediments typical of Yucca Mountain, while maintaining minimum disturbance, without the use of a truck-mounted drill rig. Even this drill rig causes some surface disturbance, and cannot drill horizontal holes.

Analysis of the data obtained from the prototype tests will be performed using analytical and numerical methods. Analytical techniques to describe vertical saturated and unsaturated flow are widely available and no development of new methodology is necessary (Hillel, 1980; Hanks and Ashcroft, 1980; Campbell, 1985). Computer simulations of the infiltration, redistribution, evapotranspiration, and drainage will be based on numerical approximations of analytical solutions. Numerical methods are required to obtain solutions for heterogeneous soil and rock units.

As mentioned previously, ponding tests will be carried out at existing or proposed neutron-access boreholes. Neutron

logging in these boreholes will be suitable for monitoring the wetting and drying of soils, nonwelded and bedded tuffs, and perhaps welded tuffs with large-fracture porosity. Neutron logging, however, may not be suitable for monitoring infiltration in rocks with small-fracture porosity. Alternative methods need to be identified and tested for monitoring water movement in these welded tuffs. For example, geotomography (Dailey and Ramirez, 1984) may be a more suitable method. Preliminary prototype ponding tests will be required to: (1) determine which logging method is most suitable for monitoring infiltration in rocks with various fracture porosities and (2) adjust methods or equipment to optimize the resolution of the selected technique. Prototype geotomography is described in detail in Section 3.1.3.3.

3.3.3.2.2 Site characterization

Ponding tests will be carried out on at least one representative site for each major geohydrologic unit on Yucca Mountain. Based on current definitions of geohydrologic-surficial units, tentative sites have been selected for ponding experiments (Table 3.3-1 and Figure 3.3-6). As soon as infiltration data become available from mapping and infiltrometer tests, a re-evaluation of the proposed ponding sites will be done to determine if they are representative of the unit as a whole, given the available information. In light of the nested process of siting the ponding tests, the number and location of these sites will probably change before site characterization begins.

3.3.3.3 Small-plot rainfall simulation

The primary purposes of the small-plot rainfall simulation (SPRS) studies are to examine the hydrologic properties of the upper 1 m (3 ft) of surficial material covering Yucca Mountain. It will also be possible, using a range in duration and intensity of precipitation applied to the soil surface, to create unsaturated conditions within the profile. Since many precipitation events on Yucca Mountain are assumed to have an intensity lower than the infiltration rate, the study of flow under unsaturated conditions is important to the characterization of the surficial sediments.

Small-plot rainfall simulation differs from large-plot rainfall simulation (LPRS) primarily in the size of the area covered and the depth of investigation. LPRS is designed to cover areas on the order of 60 m² and depths to 5 m. Depth of investigation for SPRS will be only 1 m and cover an area of 1 m². These numbers are for planning purposes and are based on standard usage. The specific size will be determined to account for local conditions and preliminary data analysis on or nearby the site. The duration of an individual test (i.e., 2 hours) and the length of time the site will be subjected (i.e., 6 months) to a series of individual tests will be based on prototype test results and preliminary analysis of all currently available data on all infiltration properties. Since more

Table 3.3-1. Proposed artificial-infiltration sites based on preliminary definitions of geohydrologic surficial units (SCP 8.3.1.2.2.1.3)

[ft, foot; approx, approximate; %, percent; SPRS, small-plot rainfall simulation; LPRS, large-plot rainfall simulation]

| | | | Site location | | | | Site description | | | Proposed testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | North (ft) | East (ft) | Approx. elevation (ft) | Slope (%) | Approx. topographic position | Estimated soil thickness (ft) | Neutron-access holes | Ponding | SPRS | LPRS |
| Tiva Canyon caprock and upper cliff | N33 | 1a | Yucca Crest south of 63 | 751,400 | 559,300 | 4,620 | 15 | Yucca Crest | 0-.1 | X | X | X | X |
| | N71 | 1b | Yucca Crest-Whale Back ridge | 761,026 | 558,406 | 4,925 | 11 | Yucca Crest | 0.5 | X | X | X | |
| | N96 | 1c | Yucca Crest Highway ridge | 759,446 | 558,403 | 4,893 | 24 | Yucca Crest | 0.2 | X | X | X | - |
| | N65 | 1d | Highway ridge | 758,627 | 562,537 | 4,372 | 14 | Ridge top 1,500 m down dip slope | 0 | X | X | - | - |
| | N74 | 1e | Yucca Crest-Whale Back ridge | 761,362 | 558,560 | 4,904 | 5 | Yucca Crest | 0-.5 | X | X | -- | -- |
| | N64 | 1f | Dead Yucca ridge | 767,800 | 559,300 | 4,760 | 10 | Dip slope-near Yucca Crest | 0 1.5 | X | X | -- | -- |
| | N94 | 1g | Yucca Crest-UE-25 UZ-6 pad | 759,724 | 558,236 | 4,926 | 0 | Yucca Crest | 0 | X | X | - | - |

Table 3.3-1. Proposed artificial-infiltration sites based on preliminary definitions of geohydrologic-surficial units (SCP 8.3.1.2.2.1.3)--Continued

[ft, foot; approx, approximate; %, percent; SPRS, small-plot rainfall simulation; LPRS, large plot rainfall simulation]

| | | | Site location | | | | Site description | | | Proposed testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | North (ft) | East (ft) | Approx. elevation (ft) | Slope (%) | Approx. topographic position | Estimated soil thickness (ft) | Neutron-access holes | Ponding | SPRS | LPRS |
| Tiva Canyon upper litho-physal | N76 | 2a | Whale Back ridge | 761,353 | 559,048 | 4,958 | 12 | Broad ridge top-dip slope | 1.5 | X | X | X | X |
| | N32 | 2b | Yucca Crest-east of N-3 | 757,200 | 559,990 | 4,610 | 15 | Narrow ridge top-dip slope | 0-1 | X | X | X | X |
| | N36 | 2c | Solitario Canyon-Yucca ridge | 765,700 | 557,675 | 4,360 | 10 | Canyon wall | 0-1.5 | X | X | X | -- |
| | N34 | 2d | Yucca Crest south of G3 | 50,150 | 559,600 | 4,380 | 15 | Channel bottom | 0-1 | X | X | -- | -- |
| | N73 | 2e | Whale Back ridge | 761,049 | 558,926 | 4,867 | 20 | Channel bottom | 0-.5 | X | X | -- | -- |
| | N53 | 2f | Dead Yucca ridge | 766,450 | 560,110 | 4,600 | 5 | Narrow ridge top-dip slope | 0-1 | X | X | -- | -- |
| Tiva Canyon clinkstone south | N66 | 3a | Highway ridge | 760,434 | 561,881 | 4,356 | 10 | Ridgetop-1,500 m down dip slope | 0 | X | X | X | X |
| | N69 | 3b | Base of Whale Back ridge | 760,860 | 562,321 | 4,228 | 27 | Canyon wall | 0 | X | X | X | X |

Table 3.3-1. Proposed artificial-infiltration sites based on preliminary definitions of geohydrologic-surficial units (SCP 8.3.1.2.2.1.3)--Continued

[ft, foot; approx, approximate; %, percent; SPRS, small-plot rainfall simulation; LPRS, large-plot rainfall simulation]

| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | Site location: North (ft) | Site location: East (ft) | Site location: Approx. elevation (ft) | Site description: Slope (%) | Site description: Approx. topographic position | Site description: Estimated soil thickness (ft) | Proposed testing: Neutron-access holes | Proposed testing: Ponding | Proposed testing: SPRS | Proposed testing: LPRS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | #31 | 3c | Middle fork of Ghost Dance wash | 757,550 | 560,450 | 4,400 | 10 | Channel bottom | 0 | X | X | -- | -- |
| | #35 | 3d | Yucca Crest south of G3 | 750,350 | 559,850 | 4,615 | 10 | Channel bottom | 0 | X | X | -- | -- |
| | #16 | 3e | Drill hole wash/Coyote wash | 765,500 | 565,300 | 4,050 | 20 | Canyon wall | 0-10 | X | X | X | X |
| Clinkstone north | #54 | 3g | Bottom of Whale Back ridge | 760,550 | 564,250 | 4,080 | 15 | Dip slope alluvium contact | 0-3 | X | X | X | X |
| Tiva Canyon lower litho-physal | #23 | 4a | Split wash | 763,973 | 564,545 | 4,043 | 27 | Canyon wall | 1 | X | X | X | -- |
| | #53 | 4b | Dead/live Yucca ridge | 766,400 | 560,100 | 4,600 | 20 | Canyon wall | 0-1 | X | X | X | -- |
| | #2 | 4c | Pagany wash | 768,606 | 566,114 | 3,947 | 48 | Canyon wall | 0 | X | X | | -- |
| | #26 | 4d | Wren wash | 768,757 | 561,023 | 4,384 | 10 | Channel bottom | 0 | X | X | | |
| | #44 | 4e | Coyote wash | 766,193 | 563,140 | 4,162 | 15 | Dip slope alluvium contact | 0-3 | X | X | -- | -- |
| | #42 | 4f | Coyote wash | 765,729 | 562,859 | 4,179 | 15 | Channel bottom | 0 | X | X | X | |

Table 3.3-1. Proposed artificial-infiltration sites based on preliminary definitions of geohydrologic-surficial units (SCP 8.3.1.2.2.1.3) -Continued

[ft, foot; approx, approximate; %, percent; SPRS, small-plot rainfall simulation; LPRS, large-plot rainfall simulation]

| | | | Site location | | | | Site description | | | Proposed testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | North (ft) | East (ft) | Approx. elevation (ft) | Slope (%) | Approx. topographic position | Estimated soil thickness (ft) | Neutron-access holes | Ponding | SPRS | LPRS |
| Tiva Canyon hackley and columnar | N25 | 5a | Wren wash | 768,430 | 561,219 | 4,335 | 10 | Channel bottom | 0 | X | X | -- | -- |
| | N61 | 5b | Abandoned wash | 755,550 | 560,150 | 4,360 | 15 | Canyon wall | 0-.5 | X | X | X | X |
| | N27 | 5c | Drillhole wash | 770,450 | 562,300 | 4,500 | 5 | Dip slope-alluvium contact | 0-3 | X | X | X | X |
| | N48 | 5d | Whale Back ridge near UT 2 | 760,835 | 562,414 | 4,211 | 20 | Canyon wall | 0 | X | X | -- | -- |
| | N24 | 5e | Wren wash | 768,005 | 562,054 | 4,226 | 10 | Channel bottom | 0 | X | X | -- | -- |
| | N62 | 5f | Abandoned wash | 755,350 | 560,300 | 4,280 | 10 | Center of channel | 0 | X | X | -- | -- |
| | N63 | 5g | Abandoned wash | 755,550 | 560,450 | 4,320 | 15 | Canyon wall adjacent to Ghost Dance fault | 0 | X | X | -- | -- |
| Topopah Springs-brick | N15 | 6a | Solitario Canyon | 760,150 | 556,600 | 4,260 | 15 | Canyon wall | 0-3 | X | X | X | X |
| Grayish red litho-physal | N11 | 6b | Solitario Canyon/west of Yucca ridge | 760,000 | 556,400 | 4,220 | 15 | Canyon wall | 0-3 | X | X | X | -- |

Table 3.3-1. Proposed artificial infiltration sites based on preliminary definitions of geohydrologic-surficial units (SCP 8.3.1.2.2.1.3)--Continued

[ft, foot; approx, approximate; %, percent; SPRS, small-plot rainfall simulation; LPRS, large-plot rainfall simulation]

| | | | Site location | | | | Site description | | | Proposed testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | North (ft) | East (ft) | Approx. elevation (ft) | Slope (%) | Approx. topographic position | Estimated soil thickness (ft) | Neutron-access holes | Ponding | SPRS | LPRS |
| Vitrophere | N37 | 6c | Solitario | 765,450 | 557,600 | 4,350 | 10 | Canyon wall | 0-.5 | X | X | -- | - |
| Undifferentiated | N80 | 6d | Solitario | 757,634 | 557,201 | 4,332 | 15 | Beginning of drainage channel | 0-.5 | X | X | -- | -- |
| Caprock | N58 | 6e | Abandoned wash | 754,800 | 560,650 | 4,270 | 10 | Channel terrace | 0-3 | X | X | -- | -- |
| Caprock | N57 | 6f | Abandoned wash | 754,950 | 560,500 | 4,180 | 10 | Channel bottom | 0 | X | X | -- | -- |
| Nonwelded & bedded tuffs | N38 | 7a | Solitario Canyon-west of Yucca ridge | 765,500 | 557,950 | 4,430 | 10 | Canyon wall | 0-3 | X | X | X | X |
| | N39 | 7b | Solitario Canyon-west of Yucca ridge | 765,750 | 557,950 | 4,420 | 15 | Canyon wall | 0-3 | X | X | -- | X |
| | N17 | 7c | Solitario Canyon-Yucca ridge | 759,350 | 556,250 | 4,200 | 20 | Canyon wall | 3-6 | X | X | X | |
| | N59 | 7d | Abandoned wash | 755,120 | 560,400 | 4,220 | 20 | Canyon wall | 0-3 | X | X | X | |
| | N10 | 7e | Pagany Wash | 769,869 | 564,744 | 4,038 | 0 | Channel bottom | 0 | X | X | | |

Table 3.3-1. Proposed artificial-infiltration sites based on preliminary definitions of geohydrologic-surficial units (SCP 8.3.1.2.2.1.3) Continued

[ft, foot; approx, approximate; %,percent; SPRS, small-plot rainfall simulation; LPRS, large-plot rainfall simulation]

| | | | Site location | | | | Site description | | | Proposed testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map unit | Access hole number | Site number (see Figure 3.3-6) | Ridge/Canyon | North (ft) | East (ft) | Approx. elevation (ft) | Slope (%) | Approx. topographic position | Estimated soil thickness (ft) | Neutron-access holes | Ponding | SPRS | LPRS |
| | N46 | 7f | Drillhole wash | 772,262 | 559,748 | 4,500 | 5 | Channel adjacent to Canyon wall | 0 | X | X | -- | -- |
| Alluvium colluvium | N28 | 8a | Split wash | 763,091 | 565,320 | 3,958 | 5 | Center of canyon | 45 | X | X | X | X |
| | N29 | 3f | Split wash | 762,613 | 565,173 | 3,975 | 10 | Dip slope/ colluvium contact, constant thickness soil | 1 | X | X | X | X |
| | N30 | 8b | Split wash | 762,048 | 565,233 | 3,959 | 27 | Dip slope/alluvium-colluvium contact, increasing soil thickness | 1 | X | X | X | X |
| | N19 | 8c | Split wash | 763,689 | 564,571 | 4,025 | 5 | Channel bottom over welded tuff | 2.5 | X | X | -- | -- |
| | N47 | 8d | Drillhole | 771,968 | 559,784 | 4,480 | 5 | Channel bottom | 33 | X | X | -- | -- |

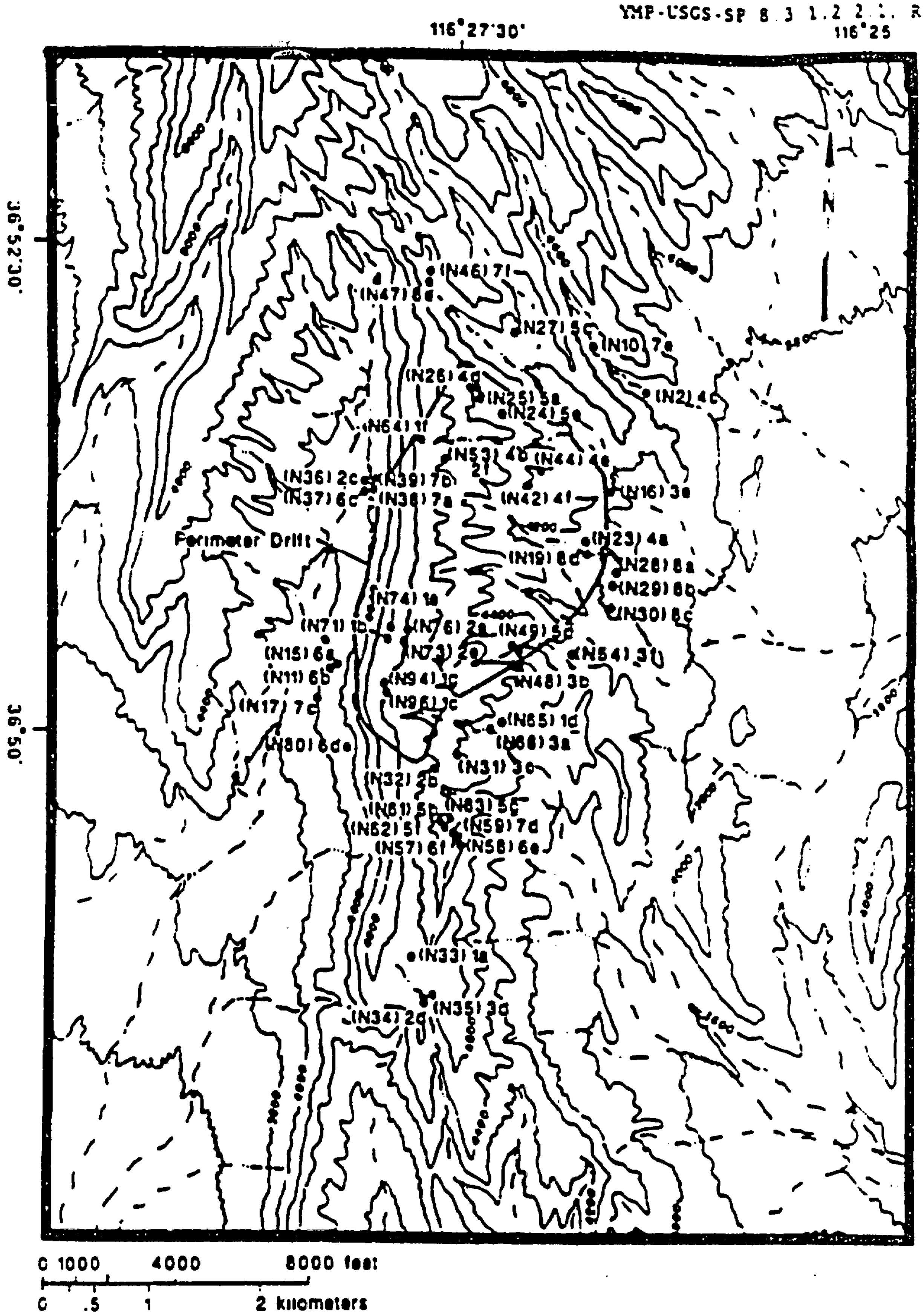


Figure 3.3-6. Map showing proposed locations of artificial-infiltration sites based on preliminary definitions of geohydrologic-surficial units.

than 80% of the bedrock above the canyon bottom of Yucca Mountain is estimated to be covered by a layer of unconsolidated rock or soil ranging thickness from less than 30 mm to 2 m, SPRS will be utilized primarily in the upland areas.

One particularly important goal in the SPRS tests will be to determine the nature of infiltration behavior at the interface between the shallow alluvial cover and the fractured bedrock. If precipitation is sufficient to fill the storage of the surface sediments, perching conditions may develop which could initiate flow into open fractures. Field data are required from each hydrologic unit to determine the complex relations between rainfall, thickness and properties of the soil, and the accumulation of perched water.

Instruments will be placed within the profile of these plots with as little disturbance as possible. All instruments and boreholes, with the exception of the neutron-access holes, will be installed in a horizontal plane beneath the test plot from an adjacent instrumentation pit (Figure 3.3-7). A control plot will also be located adjacent to each SPRS plot in an equivalent geohydrologic setting (see Section 3.2.3.2 for discussion of control plots). SPRS control plots will be instrumented in a manner similar to the test plot, but will not receive artificial rainfall. Water-content changes in the surficial material will be monitored primarily by an array of small-diameter [<10 mm (<0.4 in.)], time-domain-reflectometry (TDR) (Topp and Davis, 1982) probes installed horizontally at various depths up to one (1) m. Water-content changes in the near-surface profiles may also be monitored by neutron-moisture logging and two-borehole gamma-gamma logging in 130-mm- (5-in.-) I.D. cased boreholes. These boreholes will be located outside two adjacent sides of the plots and installed to a depth of at least 1 m (3 ft) (Figure 3.3-7). Two-borehole gamma-gamma logging may also be carried out in casing that is installed horizontally beneath the test plots. These horizontal logging boreholes are not shown in Figure 3.3-6. Preliminary tests will determine the optimum borehole configuration for two-borehole gamma-gamma logging. Preliminary tests will also determine the feasibility of using shielded sources on neutron-moisture probes to direct neutrons toward the center of the SPRS plots.

Tensiometers and heat-dissipation probes will be used for matric-potential measurements. Vacuum ground-water samplers (suction lysimeters) will be used to collect unsaturated-zone water samples. The collection of these samples will permit the monitoring of the movement of a conservative tracer introduced by artificial rainfall. Tracer-movement data will yield information on flow velocity as well as flow paths. These instruments will be installed in horizontal planes from the instrumentation pit. If possible, an organic dye similar to the one to be used in the ponding experiments will also be introduced into the artificial rainfall. After SPRS is completed, selected sites will be excavated to determine the flow paths taken by the dye tracer.

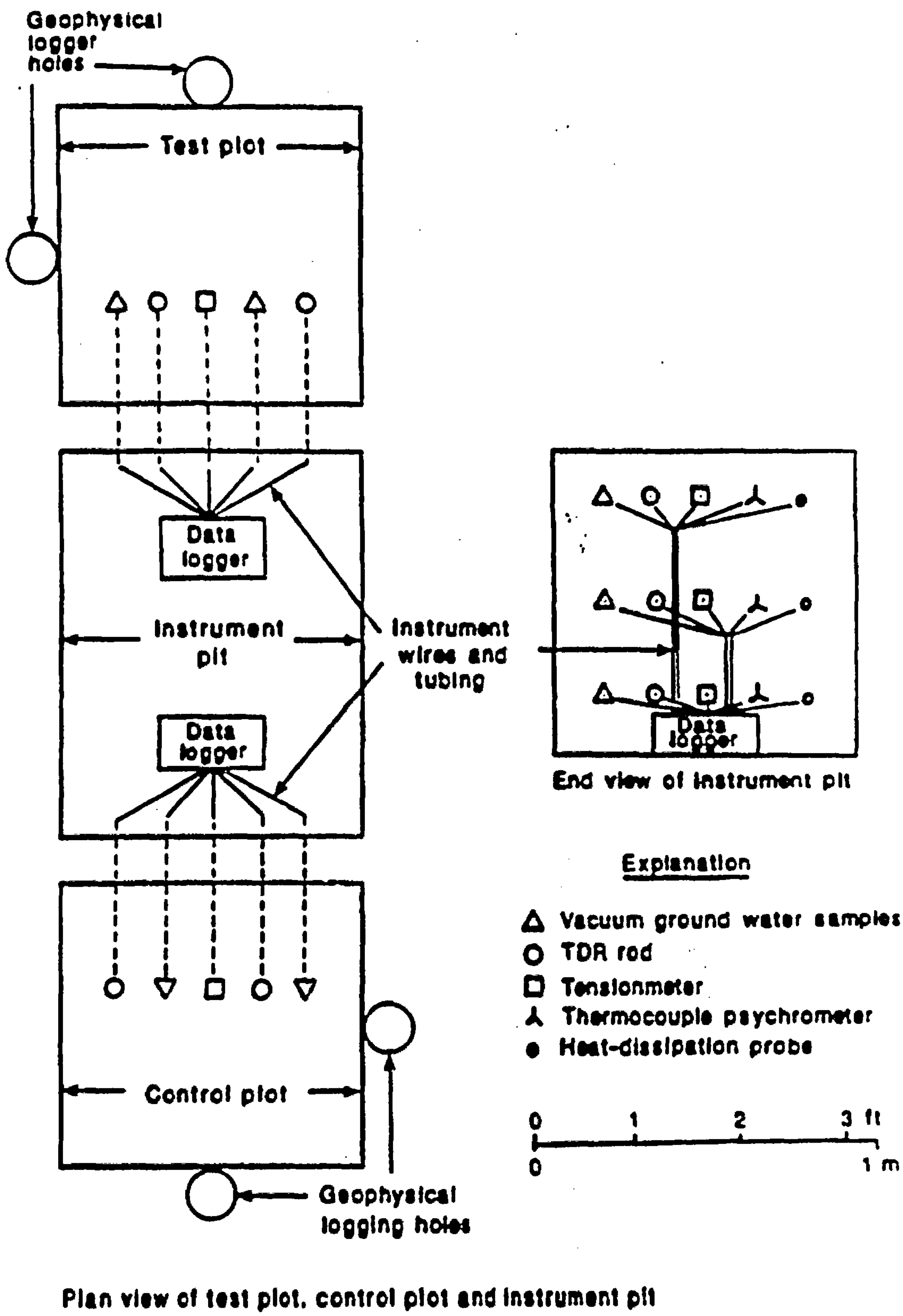


Figure 3.3-7. Schematic showing small-plot rainfall-simulation, prototype-plot design.

Boreholes in SPRS plots will be logged to depths of approximately 2 m (6 ft). At most locations, these 2 m (6 ft) boreholes will penetrate the soil and into the underlying consolidated bedrock. Water-content and water-potential sensing instruments will be installed down to 1 m (3 ft) in soil and nonwelded and bedded tuffs with a high-matrix porosity. Preliminary tests will determine the feasibility and effectiveness of installing these instruments in underlying welded tuffs of low-matrix porosity. Instruments will not be installed to depths much greater than 1 m (3 ft) primarily because flow through the side boundaries of the plots is expected to increase as depth increases. If side boundaries can be made into non-flow boundaries, useful flow-related measurements can be made to much greater depths.

A variety of rainfall events will be simulated beginning with low-intensity and short-duration storms. Infiltration will be monitored to maximum instrument depths [greater than 1 m (3 ft)]. Factors which affect the accumulation of perched water will be identified. In addition, meteorological data will be collected at each site for evapotranspiration calculations. Evapotranspiration, runoff, and precipitation data will be incorporated into water-budget calculations to attempt to estimate infiltration by different methods (Section 3.2.3.4). Runoff as a function of precipitation will be measured at each plot using flumes.

The 1-m (3-ft) thick soil profile theoretically can be wetted to different constant water contents. If this wetting is possible, values of hydraulic conductivity will be determined for each water content (Hillel, 1980). Determining changes in the water content during drainage can also provide an estimate of hydraulic conductivity (K) as a function of water content (Libardi and others 1980). In plots where matric potential can be measured reliably by tensiometers, more direct measurements of K will be made (Watson, 1966). Runoff, as a function of precipitation and infiltration, will be estimated by flumes for both control and simulation plots.

### 3.3.3.3.1 Prototype studies

Instruments for monitoring soil and infiltration parameters will be used in ponding tests done prior to SPRS prototype tests. Therefore, calibration and measurement techniques should be well understood before the start of prototype testing for SPRS. Optimum instrument installation techniques and spatial arrangement of instruments in lithologic types, such as cobbly alluvium and fractured bedrock are now being developed for use in the ponding tests. Rainfall-simulation equipment will be tested for intensity ranges and uniformity of application.

The first tests of the rainfall simulators will be performed at the prototype ponding sites. In this way, the differences between the method of water application can be quantified, at least for rainfall rates near the field saturated infiltration rate. Any problems encountered with the rainfall simulators, or

changes needed in the design will be determined during testing at the ponding sites.

A range of precipitation rates will be used during the testing of the simulator at the ponding sites. The profile will be monitored beneath the ponding plot and data will be obtained for analysis. Based on these data, a determination will be made as to the suitability of using the previously established ponding sites as supplemental SPRS sites, particularly for simulating wetter climatic conditions (the ponding site must first be allowed to go through a period of natural drainage).

After the rainfall simulator has been tested, two prototype SPRS sites will be established. The first site will be located on a relatively flat upland area and the second one where there is appreciable slope. The slope site will be needed for the testing and calibration of the runoff metering flumes.

3.3.3.3.2 Site characterization

For site characterization, it will be assumed that at least one SPRS plot will be located within each geohydrologic-surficial unit to cover the range of infiltration rates (Table 3.3-1). SPRS plots will be located adjacent to ponding sites when possible in order to obtain the highest correlation between the two types of tests. The number and locations of SPRS plots have been listed in Table 3.3-1 only for the purpose of planning. However, the number of plots listed probably represents the maximum number of SPRS plots that will be established. Results from infiltrometer, ponding and other data collection work should facilitate the combining of similar geohydrologic-surficial map units, thereby reducing the total number of plots needed.

3.3.3.4 Large-plot rainfall simulation

After completion of SPRS tests, more complex large-plot rainfall simulation (LPRS) will be carried out on at least one site in each geohydrologic unit to measure rainfall, infiltration, runoff and evapotranspiration for simulated wetter climatic conditions (Table 3.3-1). LPRS are important because a much larger ground-surface area is tested. Within one test area, a wide range of plants as well as soil surface conditions can be included and results will then represent areal averages for infiltration values. Some large plots will be sited where a thicker alluvial cover exists so that greater soil depths can be investigated.

LPRS plots will be instrumented in the same manner as the SPRS plots except for the rainfall simulator, which will initially be a trailer mounted type that can be moved from site to site. Due to the geometry of the simulator, the plot configuration will be in the form of two rectangles, as illustrated in Figure 3.3-8. The exact size of the LPRS is estimated to be 60 $m^2$, and measuring depths to 5 m is preliminary and based on site characteristics. The exact

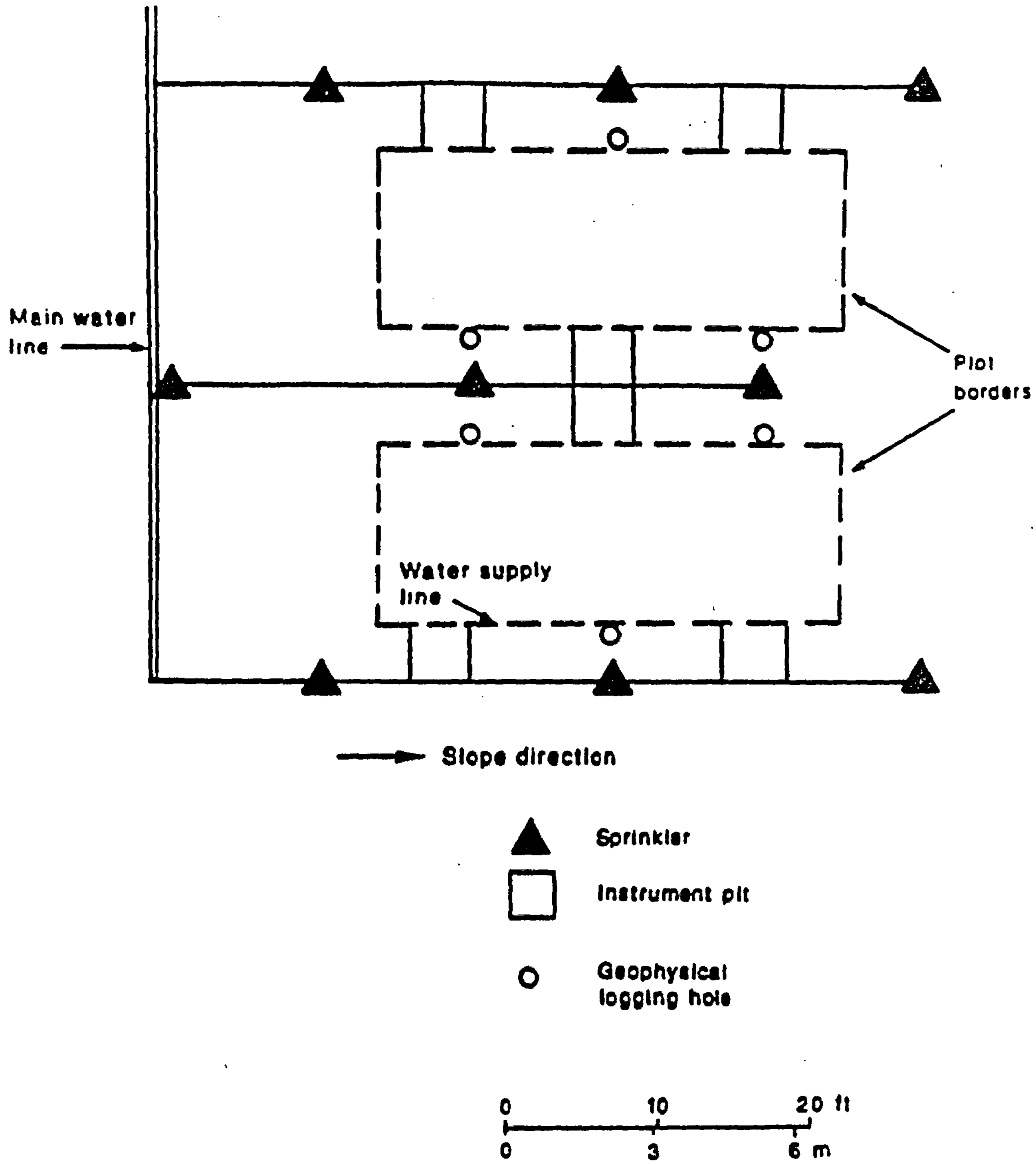


Figure 3.3-8. Schematic showing large-plot, rainfall-simulation, nine-sprinkler, paired-plot, prototype design

configuration will be determined to account for local conditions and preliminary data analysis on or nearby the site. The duration of individual tests (i.e., 8 hours) and the length of time the site will be subjected (i.e., 1 year) to a series of individual tests will be based on prototype test results and preliminary analysis of all currently available data on all infiltration properties. An alternative is the single-plot design (Figure 3.3-9) which will be evaluated during prototype development. As with ponding and SPRS sites, control plots will be established adjacent to the test plot. Methods of analysis will follow those established in SPRS.

The principal goals in the LPRS tests will be to determine the effects of measurement scale and wetter climatic conditions on the soil surface and profile. Rates of net infiltration under these wetter conditions will be of prime interest even though it will represent a bounding case since climatic changes would be expected to occur over long time periods, with corresponding increases in vegetative cover and soil development. Information from LPRS tests will be used in Study 8.3.1.5.2.2 (Characterization of future regional hydrology due to climate changes) to develop modeling techniques to predict possible future unsaturated-zone hydrologic characteristics.

#### 3.3.3.4.1 Prototype studies

The methods developed in SPRS prototype tests to install instruments and monitor water movement will be applicable to LPRS. Two sites will be established for prototype tests, one on a relatively flat surface and a second on sloping terrain.

The site configuration and procedures employed in LPRS will depend greatly on the experience gained through SPRS. Initially it is assumed that the prototype LPRS sites will differ from the SPRS sites primarily in the depth to which instrumentation will be placed.

#### 3.3.3.4.2 Site characterization

The number and locations of LPRS plots are given in Table 3.3-1. Again, the number and locations of LPRS sites will depend on the results of ponding and SPRS tests. Therefore, this number is thought to be a conservative estimate, and the actual number is expected to be less.

### 3.3.3.5 Borehole drilling and coring for artificial infiltration

Drilling and coring for artificial-infiltration studies will be similar to methods employed for the natural-infiltration studies. See Section 3.2.3.1 for a detailed discussion.

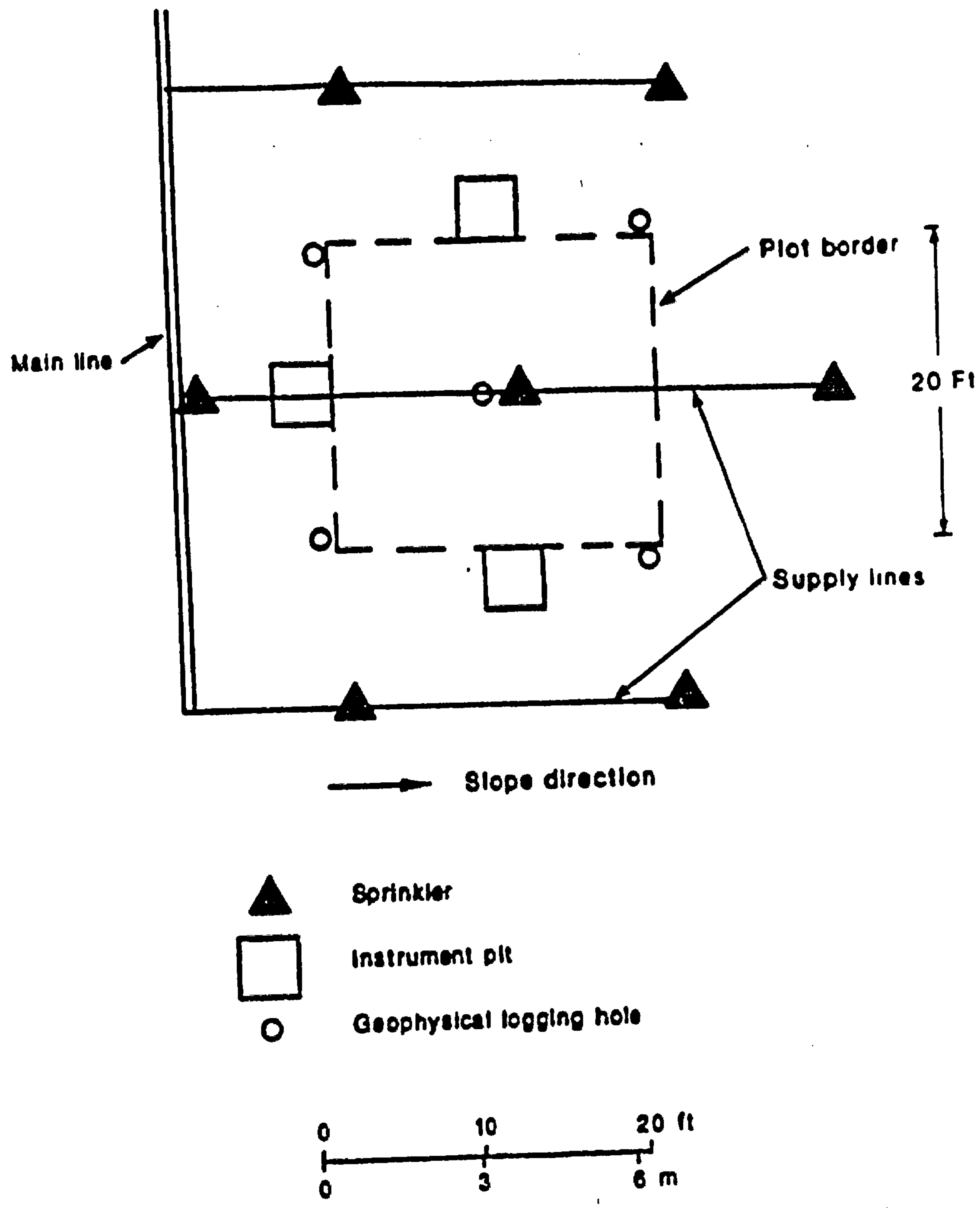


Figure 3.3-9. Schematic showing large-plot, rainfall-simulation, seven-sprinkler, single-plot prototype design.

3.3.3.6 Geostatistical analysis of the spatial variability of the artificial-infiltration parameters

The nature of artificial-infiltration parameters is such that geostatistical methods are appropriately applied to their analysis. Theory and use of geostatistics was covered in Section 3.2.3.6.

3.3.3.7 Methods summary

The parameters to be determined by the tests described above are summarized in Table 3.3-2. Also listed are the selected and alternate methods for determining the parameters and the current estimate of the parameter-value range. The alternate methods will be used if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, only the most common methods are included in the table. The selected methods in Table 3.3-2 were chosen primarily on the basis of accuracy, precision, duration of methods, expected range, and lack of interference with other tests and analyses.

The USGS investigators have selected methods which they believe are suitable to provide accurate data within the expected range of the site parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.3.4 Technical procedures

The USGS quality-assurance program plan for the YMP (USGS, 1986) requires documentation of technical procedures for all technical activities that require quality assurance.

Table 3.3-3 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a USGS procedure number and an effective date. Procedures that are not identified with an effective date will be completed and available 30 days (for standard procedures) or 60 days (for non-standard procedures) before the associated testing is started; these procedures are also identified with a "TBD" (To Be Determined) technical procedure number. Some of the listed technical procedures are primarily outside the objectives of the subject activity, but are included for general information and ease of cross referencing. Approved technical procedures not listed may be used during the activity, should that be appropriate, and listed procedures may be revised or replaced with other procedures, as needed.

Applicable quality-assurance procedures are presented in Appendix 7.1.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling,

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)

[Dashes (---) indicate information is not available or not applicable.]

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| | **Infiltrometer tests** | |
| Infiltrometer study to determine maximum artificial-infiltration rate (selected) | Maximum artificial-infiltration rate | 0 to 6 m/hour |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | " | " |
| Calculate from physical properties to determine maximum artificial-infiltration rate (alternate) | " | " |
| | **Ponding tests** | |
| Ponding studies to determine maximum infiltration rates and saturated hydraulic conductivity (selected) | Maximum infiltration rate | 0 to 6 m/hour |
| Infiltrometer study to determine maximum artificial-infiltration rate (alternate) | " | " |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | " | " |
| Calculate from physical properties maximum artificial-infiltration rate (alternate) | " | " |
| Ponding studies to determine maximum infiltration rates and saturated hydraulic conductivity (selected) | Saturated hydraulic conductivity | 0 to 1 m/hour |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Ponding tests--Continued** | | |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | Saturated hydraulic conductivity | 0 to 6 m/hour |
| Infiltrometer study to determine maximum artificial-infiltration rate (alternate) | " | " |
| Calculate from physical properties maximum artificial-infiltration rate (alternate) | Saturated hydraulic-infiltration rate | " |
| Ponding studies to determine flow pathways by tracer methods (selected) | Flow pathways | -- |
| Use environmental tracers to determine flow pathways (alternate) | " | -- |
| Model calculations using measured flow parameters to determine flow pathways (alternate) | " | -- |
| Ponding studies to determine unsaturated hydraulic conductivity by monitoring drainage using geophysical methods (selected) | Unsaturated hydraulic conductivity | 0 to 0.1 m/hour |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | " | " |
| Calculate from physical properties to determine maximum artificial-infiltration rate (alternate) | " | " |

Table 3.3-2. Summary of tests and methods for artificial-infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Small-plot, rainfall-simulation tests** | | |
| Determine maximum infiltration rates by applying increasing rates of simulated rainfall until runoff occurs (selected) | Maximum infiltration rate | 0 to 1 m/hour |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | " | 0 to 8 m/hour |
| Calculate from physical properties to determine infiltration rate (alternate) | " | " |
| Infiltrometer study to determine maximum artificial-infiltration rate (alternate) | " | " |
| Determine saturated hydraulic conductivity by increasing rates of simulated rainfall (selected) | Saturated hydraulic conductivity | " |
| Computer modeling of physical properties to determine saturated hydraulic conductivity (alternate) | " | " |
| Laboratory analysis of cores to determine saturated hydraulic conductivity (alternate) | " | " |
| Determine flow pathways by tracer method (selected) | Flow pathways | -- |
| Use environmental tracers to determine flow pathways (alternate) | " | -- |
| Model calculations using measured flow parameters to determine flow pathways (alternate) | " | -- |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Small-plot, rainfall-simulation tests--Continued** | | |
| Determine flow velocities by tracer method (selected) | Flow velocity | 0 to 1m/hour |
| Determine artificially induced, rainfall-runoff-infiltration relations by rainfall simulation under different hydrologic initial conditions (selected) | Rainfall-runoff- infiltration relations | -- |
| Determine rainfall- runoff-infiltration relations by computer modeling of physical properties (alternate) | " | -- |
| Determine rainfall- runoff-infiltration relations from natural infiltration only (alternate) | " | -- |
| Determine unsaturated hydraulic conductivity by increasing rates of simulated rainfall (selected) | Unsaturated hydraulic conductivity | 0 to 6m/hour |
| Computer modeling of physical properties to determine unsaturated hydraulic conductivity (selected) | " | " |
| Laboratory analysis of cores to determine unsaturted hydraulic conductivity (selected) | " | " |
| Measure density profiles by laboratory analysis of continuous core samples (selected) | Bulk density | 1 to 2.6g/cm$^3$ |
| Measure density profiles by gamma-gamma logging (selected) | " | " |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Small-plot, rainfall-simulation tests--Continued** | | |
| Measure porosity by displacement method (selected) | Porosity | 0.05 to 0.60 $cm^3/cm^3$ |
| Calculate porosity from density values (selected) | " | " |
| Measure water-content profiles by neutron-moisture logging (selected) | Water-content profiles | 1 to 60% $cm^3/cm^3$ |
| Measure water-content profiles by other geophysical-logging methods (e.g., gamma-gamma, neutron porosity) (selected) | " | 1 to 60% |
| Measure water-content profiles by collecting and analyzing core (selected) | " | " |
| Determine water-potential profiles by tensiometer-transducer and heat-dissipation probe methods (selected) | " | 0 to -300 kPa (current lower limit of heat-dissipation probes) |
| **Large-plot, rainfall-simulation tests** | | |
| Determine maximum infiltration rates by applying increasing rates of simulated rainfall until runoff occurs (selected) | Maximum infiltration rate | 0 to 1 m/hour |
| Calculate geophysical properties to determine maximum artificial-infiltration rate (alternate) | " | 0 to 6 m/hour |
| Infiltrometer study to determine maximum artificial-infiltration rate (alternate) | " | " |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| *Large-plot, rainfall-simulation tests--Continued* | | |
| Laboratory analysis of cores to determine maximum artificial-infiltration rate (alternate) | Maximum infiltration rate | 0 to 6 m/hour |
| Determine saturated hydraulic conductivity by increasing rates of simulated rainfall (selected) | Saturated hydraulic conductivity | " |
| Computer modeling of physical properties to determine saturated hydraulic conductivities (alternate) | " | " |
| Laboratory analysis of cores to determine saturated hydraulic conductivity (alternate) | " | " |
| Determine flow pathways by tracer method (selected) | Flow pathways | -- |
| Use environmental tracers to determine flow pathways (alternate) | " | -- |
| Model calculations using measured flow parameters to determine flow pathways (alternate) | " | -- |
| Determine artificially induced rainfall-runoff-infiltration relations by rainfall simulation under different hydrologic initial conditions (selected) | Rainfall-runoff-infiltration relations | -- |
| Determine rainfall-runoff-infiltration relations by computer modeling of physical properties (alternate) | " | -- |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| | Large-plot, rainfall-simulation tests--Continued | |
| Determine rainfall-runoff-infiltration relations from natural rainfall only (alternate) | Rainfall-runoff-infiltration relations | - |
| Determine unsaturated hydraulic conductivity by increasing rates of simulated rainfall (selected) | Unsaturated hydraulic conductivity | 0 to cm/hour |
| Computer modeling of physical properties to determine unsaturated hydraulic conductivity (selected) | " | " |
| Laboratory analysis of cores to determine unsaturated hydraulic conductivity (selected) | " | " |
| Measure density profiles by laboratory analysis of continuous core samples (selected) | Bulk density | 1 to 2.6g/$cm^3$ |
| Measure density profiles by gamma-gamma logging (selected) | " | " |
| Measure porosity by displacement method (selected) | Porosity | 0.05 to 0.60 $cm^3/cm^3$ |
| Calculate porosity from density values (selected) | " | " |
| Measure water-content profiles by neutron-moisture logging (selected) | Water-content profiles | 1 to 60% $cm^3/cm^3$ |
| Measure water-content profiles by other geophysical-logging methods (e.g., gamma-gamma, neutron porosity) (selected) | " | 1 to 60% |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| **Large-plot, rainfall-simulation tests--Continued** | | |
| Measure water-content profiles by collecting and analyzing core (selected) | Water-content profiles | 1 to 60% |
| Determine water-potential profiles by tensiometer-transducer and heat-dissipation probe methods (selected) | " | 0 to -300 kPa (current lower limit of heat-dissipation probes) |
| **Borehole drilling and coring from artificial-infiltration studies** | | |
| Use air-rotary coring methods to core consolidated material for artificial-infiltration studies (selected) | -- | -- |
| Use drive-core method to core unconsolidated material for artificial- infiltration studies (selected) | -- | -- |
| Use Odex drilling method to drill holes for artificial-infiltration studies (selected) | -- | -- |
| Use rotary core using liquids to core consolidated materials for artificial-infiltration studies (alternate) | -- | -- |
| Use Shelby tube, pitcher core barrel, or Dennison core barrel to core unconsolidated material for artificial- infiltration studies (alternate) | -- | -- |
| Use rotary drilling, auger drilling, or percussion hammer to drill holes for artificial-infiltration studies (alternate) | -- | -- |

Table 3.3-2. Summary of tests and methods for artificial infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Methods (selected and alternate) | Site parameter | Range |
|---|---|---|
| Geostatistical analysis of the spatial variability of the artificial-infiltration parameters | | |
| Geostatistical analysis to determine the spatial variability of artificial-infiltration parameters (selected) | Spatial variability of artificial-infiltration parameters | -- |

Table 3.3-3. Technical procedures assignments for artificial-infiltration activity (SCP 8.3.1.2.2.1.3)
(Dashes (--) indicate information is not available and to be determined.

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Infiltrometer measurements** |
| *80 | Methods for determining maximum artificial-infiltration rates using infiltrometers |
| | **Ponding tests** |
| HP-12 | Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS |
| HP-55 | Hydrologic-laboratory testing of core and drill-cutting samples from unsaturated-zone test holes |
| HP-121 | Installing and retrieving information from a Setra pressure transducer |
| HP-136 | Methods for handling and storage of drill cuttings and core from unsaturated-zone boreholes at the unsaturated-zone testing laboratory (Test Cell C) |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |
| | **Small-plot, rainfall simulation** |
| HP-15 | Method for calibrating heat-dissipation sensors for measuring in-situ matric potential within porous media |
| HP-17 | Method of calibration and testing for operation of pressure transducers for air-permeability studies in the unsaturated zone |

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Table 3.3-3. Technical procedures assignments for artificial-infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Small-plot, rainfall simulation--Continued** |
| HP-69 | Construction and operation of simple tensiometers |
| HP-88 | Preliminary method of chemical/hydrological study of alluvium around Yucca Mountain using small-plot rainfall simulation devices |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |
| | **Large-plot, rainfall simulation** |
| HP-14 | Method for calibrating Peltier-type thermocouple psychrometers for measuring water potiental of partially-saturated media |
| HP-15 | Method for calibrating heat-dissipation sensors for measuring in-situ matric potential within porous media |
| HP-17 | Method of calibration and testing for operation of pressure transducers for air-permeability studies in the unsaturated zone |
| HP-62 | Method for measuring sub-surface moisture content using a neutron moisture meter |
| | **Borehole drilling and coring for artificial-infiltration** |
| HP-12 | Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS |

Table 3.3-3. Technical procedures assignments for artificial-infiltration activity (SCP 8.3.1.2.2.1.3)--Continued

| Technical procedure number (NWM-USGS-) | Technical procedure |
|---|---|
| | **Geostatistical analysis of the spatial variability of artificial-infiltration parameters--Continued** |
| TBD | Characterization of spatial variability of artificial-infiltration parameters |

and calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

# 4 APPLICATION OF STUDY RESULTS

## 4.1 Application of results to resolution of design and performance issues

The results of this study will be used in the resolution of YMP performance and design issues concerned with fluid flow within the unsaturated zone beneath Yucca Mountain. The principal applications will be in assessments of total system performance and ground-water travel times (Issues 1.1 and 1.6). Also, results from this study will provide input into design analyses related to the waste package (Issue 1.10) and near-field environment (Issue 1.5), and underground repository facilities (Issue 1.11 and 4.4). Issues concerned with repository seals (Issue 1.12) and worker and public radiological safety (Issues 2.2, 2.7, 2.1, and 2.3) will also use the hydrologic information resulting from this study.

The application of site information from this study to design- and performance-parameter needs required for the resolution of design and performance issues is addressed in Section 1.3. Sections 2 and 3 use logic diagrams and tables to summarize specific relations between performance- and design-parameter needs and site parameters determined from this study.

## 4.2 Application of results to support other site-characterization investigations and studies

Data collected in this study will be employed in other studies in Investigation 8.3.1.2.2 (Description of the unsaturated-zone hydrologic system at the site), as well as studies in the following investigations:

- 8.3.1.2.1 - Studies to provide a description of the regional hydrologic system;
- 8.3.1.3.7 - Studies to provide the information required on radionuclide retardation by all processes along flow paths to the accessible environment;
- 8.3.1.4.2 - Geologic framework of the Yucca Mountain site;
- 8.3.1.4.3 - Development of three-dimensional models of rock characteristics at the repository site;
- 8.3.1.5.1 - Studies to provide the information required on nature and rates of change in climatic conditions to predict future climates;
- 8.3.1.5.2 - Studies to provide the information required on potential effects of future climatic conditions on hydrologic characteristics;
- 8.3.1.6.2 - Potential effects of future climatic conditions on locations and rates of erosion;
- 8.3.1.12.1 - Studies to provide data on regional meteorological conditions;
- 8.3.1.17.3 - Studies to provide required information on vibratory ground motions that could affect repository design or performance;
- 8.3.1.17.4 - Preclosure tectonics data collection and analysis;
- 8.3.5.12.2 - Calculational models to predict ground-water travel times between the disturbed zone and accessible environment; and
- 8.3.5.13.1 - Site information needed to calculate the releases to the accessible environment.

Surficial-materials, hydrologic-, and physical-property data obtained from activities in this study will be applicable to a number of site-characterization investigations. For example, detailed fracture data on outcropping-bedrock units obtained from geotomography, shallow surface-seismic surveys, the excavation of selected artificial-infiltration plots, and core from infiltration-related boreholes will add to the fracture data base generated from Investigations 8.3.1.17.3 (Studies to provide required information on vibratory ground motions that could affect repository design or performance) and 8.3.1.4.2 (Geologic framework of the Yucca Mountain site). Porosity and density data obtained from the nuclear (geophysical)

logging of infiltration-related boreholes will also be useful in the analysis of rock properties. Information on the soils of upland areas of Yucca Mountain obtained from the sampling, testing, and mapping of surficial materials will provide an adequate data base for Investigation 8.3.1.5.2 (Studies to provide the information required on potential effects of future climate conditions on hydrologic characteristics). Remote-sensing techniques developed by Activity 8.3.1.2.2.1.1 will be used in conjunction with Studies 8.3.1.5.2.1 (Characterization of the Quaternary regional hydrology), 8.3.1.17.4.7 (Subsurface geometry and concealed extensions of Quaternary faults at Yucca Mountain), and 8.3.1.2.1.3 (Characterization of the regional ground-water flow system). Data collection from these studies will provide support for estimating values of potential infiltration (Activity 8.3.1.2.2.1.1), potential discharge (Activity 8.3.1.5.2.1.3), and for delineating regional fracture-zone hydrology (Activity 8.3.1.17.4.7.7). These data will also be used to support regional saturated-zone and paleohydrologic modeling (indirectly through Study 8.3.1.2.1.3).

Studies 8.3.1.2.1.1 (Characterization of the meteorology for regional hydrology), 8.3.1.5.2.2 (Characterization of the future regional hydrology due to climate changes), 8.3.1.5.1.1 (Characterization of modern regional climate), and 8.3.1.12.1.1 (Characterization of the regional meteorological conditions) will employ data generated by Activity 8.3.1.2.2.1.2 (Evaluation of natural infiltration). Information from LPRS tests will be used in Study 8.3.1.5.2.2 to develop modeling techniques to predict possible future unsaturated-zone hydrologic characteristics. Studies 8.3.1.6.2.1 (Influence of future climatic conditions on locations and rates of erosion) and 8.3.1.2.1.2 (Characterization of runoff and streamflow) will utilize rainfall-runoff data obtained from sampling, testing, and mapping and artificial-infiltration activities. Also, measurement of flux, other than that obtained from the natural and artificial-infiltration activities, will be independently estimated from environmental tracers. Concentration profiles for water extracted from core samples over the entire thickness of the unsaturated zone will yield data useful in Study 8.3.1.2.2.7 (Hydrochemical characterization of the unsaturated zone).

Finally, flux-related data and lithologic characteristics generated by the infiltration studies will be synthesized into a three-dimensional model of the unsaturated-zone hydrologic system and its interaction with the saturated-zone system (Study 8.3.1.2.2.8, Fluid flow in unsaturated, fractured rock; Study 8.3.1.2.2.9, Site unsaturated-zone modeling and synthesis; and Investigation 8.3.1.4.3, Development of three-dimensional models of rock characteristics at the repository site).

# 5 SCHEDULES AND MILESTONES

## 5.1 Schedules

The proposed schedule presented in Figure 5.1-1 summarizes the logic network and reports for the three activities of the unsaturated-zone infiltration study. This figure represents a summary of the schedule information which includes the sequencing, interrelations, and relative durations of the activities described in this study. In particular, the activities described in this study will be dependent on the construction schedules of the neutron-access boreholes and the artificial-infiltration plots.

Specific durations and start and finish dates for the activities are being developed as part of ongoing planning efforts. The development of the schedule for this study has taken into account how the study will be affected by contributions of data or interferences from other studies, and also how the present study will contribute or may interfere with other studies.

Accurate characterization of unsaturated-zone percolation will require several years of hydrologic testing and monitoring. Because of the relatively long period of time needed, the planned activities provide little time for delay.

The time allotted to establish the infiltration site (i.e., less than three months), and run preliminary infiltration experiments (i.e., 1 year) is believed to be adequate to establish a baseline of information on infiltration properties and processes based on experience in other field infiltration studies. Longer term analyses, as proposed in Figure 5.1-1, will be used to further investigate infiltration properties and processes under varying climatic conditions. Although this information will be valuable to the understanding of infiltration, the time required may be reduced if time constraints or project needs dictate. One full year of monitoring will be required to sample infiltration under winter and summer conditions. The long-term monitoring requirements are more directed to the control plots in support of the natural infiltration studies, Section 3.2.3.2. Longer term monitoring in support of natural infiltration may be required depending on the change of environmental conditions.

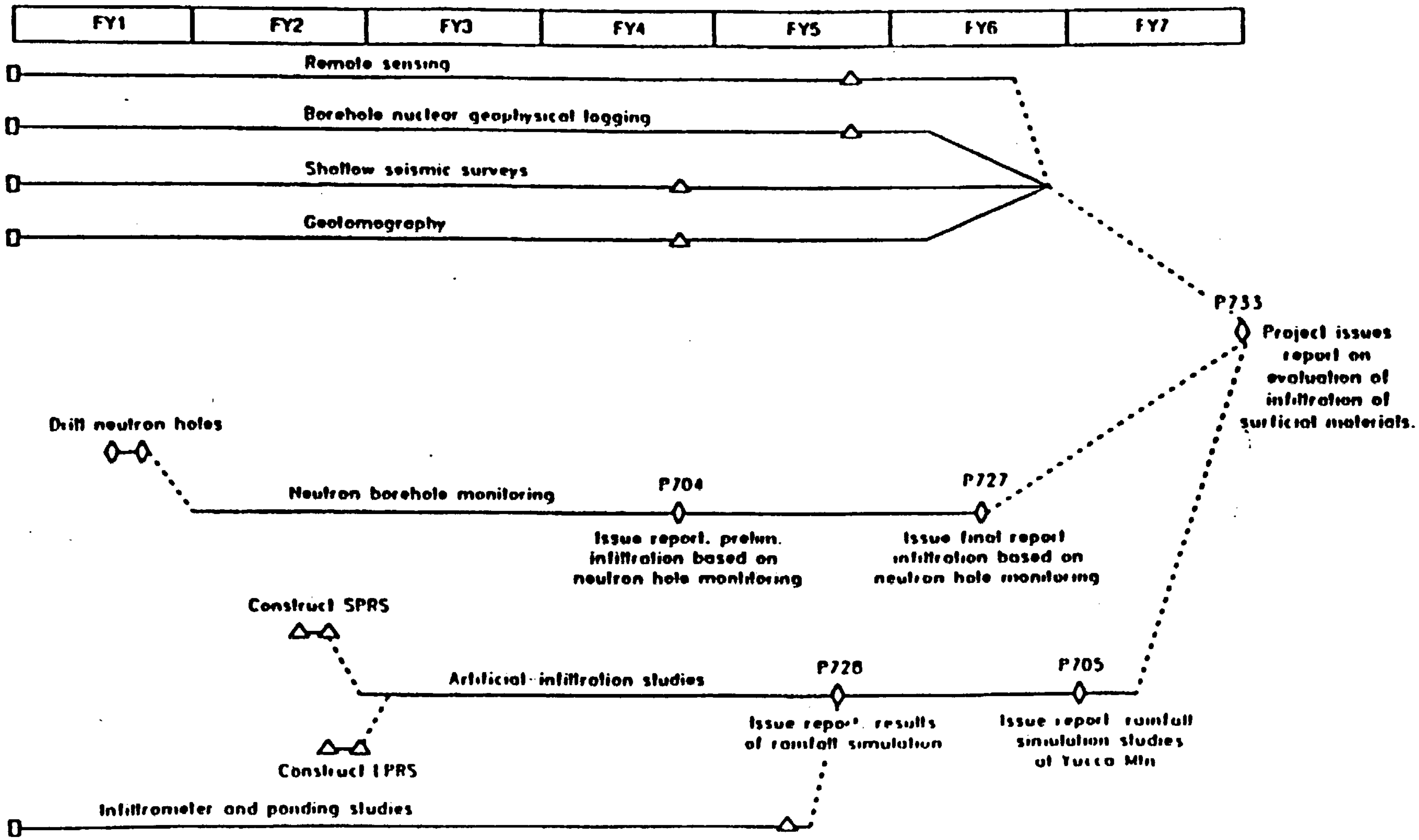


Figure 5.1-1. Summary network for unsaturated-zone infiltration study

## 5.2 Milestones

The level, number, and title of milestones associated with the three activities of the characterization of unsaturated-zone infiltration study are summarized in Table 5.2-1.

The information presented in Table 5.2-1 represents major events or important summary milestones associated with the activities presented in this study plan. Specific dates for the milestones are not included in the tables, as project schedules have been revised from those originally stated in Section 8.5 of the SCP, and are subject to further change due to ongoing planning efforts.

Table 5.2-1. Milestone list for work-breakdown structure number [illegible] (SCP 8.3.1.2.2.1)

[ Milestone dates are unavailable at this time ]

| Milestone number | Milestone | Milestone level |
|---|---|---|
| Characterization of unsaturated-zone infiltration: 8.3.1.2.2.1 | | |
| P735 | Project issues report on evaluation of infiltration rates of surficial materials | 1 |
| [illegible]385 | Project issues report on the preliminary evaluation of infiltration rates of surficial materials for input to DEIS | 1 |
| Evaluation of natural infiltration: 8.3.1.2.2.1.2 | | |
| P704 | Issue report: Preliminary infiltration based on neutron hole monitoring | 2 |
| P727 | Issue final report: Infiltration based on neutron hole monitoring | 2 |
| Evaluation of artificial infiltration: 8.3.1.2.2.1.3 | | |
| P705 | Issue report: Rainfall simulation studies at Yucca Mountain | 2 |
| P728 | Issue report: Results of rainfall simulation studies | 2 |

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# 7 APPENDICES

## 7.1 Quality-assurance requirements

### 7.1.1 Quality-assurance requirements matrix

Determination of the quality status for the activities of this study will be made separately, according to AP-6.17Q, "Determination of the Importance of Items and Activities", which implements NUREG-1318, "Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to Quality Assurance Requirements". The results of that determination will be contained in the Q-List, Quality Activities List and Non-Selection Record, which will be controlled documents.

QA grading packages for the activities of this study plan will be prepared separately, according to AP-5.28Q, "Quality Assurance Grading". The resultant Quality Assurance Grading Report will be issued as a controlled document.

Applicable NQA-1 criteria for Study 8.3.1.2.2.1 and how they will be satisfied

| NQA-1 Criteria # | Documents addressing these requirements |
|---|---|
| 1. Organization and interfaces | The organization of the OCRWM program is described in the Mission Plan (DOE/RW-005, June 1985) and further described in Section 8.6 of the SCP. Organization of the USGS-YMP is described in the following:<br><br>QMP-1.01 (Organization Procedure) |
| 2. Quality-assurance program | The Quality-Assurance Programs for the OCRWM are described in YMP-QA Plan-88-9, and OGR/83, for the Project Office and HQ, respectively. The USGS QA Program is described in the following:<br><br>QMP-2.01 (Management Assessment of the YMP-USGS Quality-Assurance Program)<br><br>QMP-2.02 (Personnel Qualification and Training Program)<br><br>QMP-2.05 (Qualification of Audit and Surveillance Personnel)<br><br>QMP-2.06 (Control of Readiness Review) |

| | |
|---|---|
| | QMP-2.07 (Development and Conduct of Training)<br><br>Each of these QA programs contains Quality Implementing Procedures further defining the program requirements. An overall description of the QA Program for site characterization activities is described in Section 8.6 of the SCP. |
| 3. Scientific investigation control and design | This study is a scientific investigation. The following QA implementing procedures apply:<br><br>QMP-3.02 (USGS QA Levels Assignment [QALA])<br><br>QMP-3.03 (Scientific and Engineering Software)<br><br>QMP-3.04 (Technical Review of YMP-USGS Publications)<br><br>QMP-3.05 (Work Request for NTS Contractor Services [Criteria Letter])<br><br>QMP-3.06 (Scientific Investigation Plan)<br><br>QMP-3.07 (Technical Review Procedure)<br><br>QMP-3.09 (Preparation of Draft Study Plans)<br><br>QMP-3.10 (Close-out Verification for Scientific Investigations)<br><br>QMP-3.11 (Peer Review) |
| 4. Administrative operations and procurement | QMP-4.01 (Procurement Document Control)<br><br>QMP-4.02 (Acquisition of Internal Services) |
| 5. Instructions, procedures, plans, and drawings | The activities in this study are performed according to the technical procedures listed in Section 3 of this study plan, and the QA administrative procedures referenced in this table for criterion 3.<br><br>QMP-5.01 (Preparation of Technical Procedures)<br><br>QMP-5.02 (Preparation and Control of Drawings and Sketches) |

| | |
|---|---|
| | QMP-5.03 (Development and Maintenance of Management Procedures) |
| | QMP-5.04 (Preparation and Control of the USGS QA Program Plan) |
| 6. Document control | QMP-6.01 (Document Control); |
| 7. Control of purchased items and services | QMP-7.01 (Supplier Evaluation, Selection and Control) |
| 8. Identification and control of items, samples, and data | QMP-8.01 (Identification and Control of Samples) |
| | QMP-8.03 (Control of Data) |
| 9. Control of processes | Not applicable |
| 10. Inspection | Not applicable |
| 11. Test control | Not applicable |
| 12. Control of measuring and test equipment | QMP-12.01 (Instrument Calibration) |
| 13. Handling, shipping, and storage | QMP-13.01 (Handling, Storage, and Shipping of Instruments) |
| 14. Inspection, test, and operating status | Not applicable |
| 15. Control of nonconforming items | QMP-15.01 (Control of Nonconforming Items) |
| 16. Corrective action | QMP-16.01 (Control of Corrective Action Reports) |
| | QMP-16.02 (Control of Stop-Work Orders) |
| | QMP-16-03 (Trend Analysis) |
| 17. Records management | QMP-17.01 (YMP-USGS Records Management) |

| | | |
|---|---|---|
| | | QMP-17.02 (Acceptance of Data Not Developed Under the YMP QA Plan) |
| 18. | Audits | QMP-18.01 (Audits) |
| | | QMP-18.02 (Surveillance) |

## 7.2 Relations between the site information to be developed in this study and the design and performance information needs specified in the SCP

This section tabulates in Table 7.2-1 the specific technical information relations between SCP design- and performance-parameters needs and site parameters to be determined in this study. The relations were developed using model-based parameter categories (see Figure 2.1-1) that provide common terminology and organization for evaluation of site, design, and performance information relations.

All design and performance issues that obtain data from this study are noted in the table. For each issue, the site parameters (from SCP 8.3.1.2) are related to the design and performance parameters reported in the performance allocation tables (from SCP 8.3.2 - 8.3.5). At the beginning of each issue group, the performance measures addressed by the design or performance parameters for the issue are listed. Parameter categories, as noted above, are used to group the design and performance parameters with the site parameters so that comparisons of information requirement (design and performance) with information source (site study) can be made.

For each design and performance parameter noted in the table, the associated goal and confidence (current and needed) and site location are listed. For each parameter category, the associated site parameters are listed with information about the site location and the site activity providing the information.

Note - Comparison of the information relations (site parameters with design/performance parameters) must be done as sets of parameters in a given parameter category. Line-by-line comparisons from the left side of the table (design/performance parameters) with the right side of the table (site parameters) within a parameter category should not be made.

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.1** | **Total system performance** | | | | (SCP 8.3.5.13) |

Performance Measures: (Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases.)
EPPM[a], disturbed case C-1, increased water flux through unsaturated zone
EPPM[a], nominal case, release scenario class E, water pathway release

Parameter Category: Fracture distribution

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Fracture frequency (Fracture networks) | Controlled area; All units | Goal: Mean, Variance, Autocorrelation length<br>Current: Low, Low, Low<br>Needed: Medium, Low, Low | Fracture density | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |

Parameter Category: Surface-water flood and runoff characteristics

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Expected magnitude of local flux change, and quantitative bounds on magnitude of flux change, due to flooding through access shafts (scenario class C-1, local or extensive increases in unsaturated zone percolation flux) | Shaft locations; Land surface | Goal: Show <25,000 $m^3$ per yr would pass through access shafts<br>Current: Low<br>Needed: Medium | Correlation of surficial materials properties with spectral responses | - | - |
| | | | Infiltration runoff map units | - | - |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.1 | Total system performance | | | | (SCP 8.3.5.13) |
| Performance Measures: (Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases.) EPPM[a], nominal case, release scenario class E, water pathway release | | | | | |
| **Parameter Category: Surface-water flood and runoff characteristics** | | | | | |
| | | | Rainfall-runoff-infiltration relations | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1.3 |
| **Parameter Category: Unsaturated zone transmissive properties** | | | | | |
| Relative liquid permeability (wetting and draining) (Rock matrix) | Repository area; Unsaturated-zone units, overburden | Goal: Mean, Variance<br>Current: NA, NA<br>Needed: Medium, Low | Saturated hydraulic conductivity | Yucca Mountain; Surficial soils and bedrock exposures, hydrogeologic and bedrock units | " |
| Relative liquid permeability (wetting and draining) (fracture network) | " | Goal: Mean, Variance<br>Current: NA, NA<br>Needed: Low, Low | Unsaturated hydraulic conductivity | " | " |
| Effective porosity (Rock matrix) | " | Goal: Mean, Variance, Autocorrelation length<br>Current: NA, NA, NA<br>Needed: High, Medium, Low | | | |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.1 | Total system performance | | | | (SCP 8.3.5.13) |
| Performance Measures: EPPM[a], nominal case, release scenario class E, water pathway release (Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases.) | | | | | |
| Parameter Category: Unsaturated zone storage properties | | | | | |
| $n_e$: average effective matrix porosity, repository area unsaturated zone (scenario class E, nominal case)[b] | Repository area; Unsaturated zone | Goal: >0.1<br>Current: Low<br>Needed: High | Porosity | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Moisture retention (wetting and draining) (Rock matrix) | Repository area; Unsaturated-zone units, overburden | Goal: Mean, Variance<br>Current: Medium, Medium<br>Needed: Low, Low | " | " | 8.3.1.2.2.1.3 |
| Moisture retention (wetting and draining) (Fracture network) | " | Goal: Mean, Variance<br>Current: NA<br>Needed: Low, Low | | | |
| Parameter Category: Unsaturated zone fluid flux | | | | | |
| $q_u$: average flux through repository area in unsaturated zone (scenario class E, nominal case)[b] | Repository area; Unsaturated zone | Goal: <0.5 mm/yr<br>Current: Medium<br>Needed: High | Evapotranspiration | Yucca Mountain, Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | 8.3.1.2.2.1.2 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.1 | Total system performance | | | | (SCP 8.3.5.13) |
| Performance Measures: | | | | | |
| **Parameter Category: Unsaturated zone fluid flow** | | | | | |
| | | | Infiltration rates, net | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | Infiltration rates, surface | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | " |
| | | | Flow velocity | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| | | | Maximum artificial infiltration rate | " | " |
| | | | Maximum infiltration rate | " | " |
| | | | Saturated hydraulic infiltration rate | " | " |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.5 | Waste package and repository engineered barrier system release rates | | | | (SCP 8.3.5.10) |
| Performance Measures: Concentrations of radionuclide species in gas phase, liquid water, and adsorbed to solid phases within the near field host rock. | | | | | |
| Parameter Category: Unsaturated zone transmissive properties | | | | | |
| Host-rock hydrologic properties (waste package environment) | Primary area; TSw2 | Goal: Properties known with accuracy sufficient to calculate differences in flow through the near-field rock resulting from anticipated and unanticipated events<br>Current: Low<br>Needed: High | Saturated hydraulic conductivity | Yucca Mountain; Sunficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| | | | Unsaturated hydraulic conductivity | " | " |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground-water travel time | | | (SCP 8.3.5.12) | |
| Performance Measures: (Supporting parameters used in calculating performance parameters for ground-water travel time.)<br>Boundary of repository-induced changes in effective fracture porosity<br>Ground-water travel time[e], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[e], Calico Hills non welded, vitric unit (primary reliance)<br>Ground-water travel time[e], Calico Hills non welded, zeolitized unit (primary reliance) | | | | | |
| **Parameter Category: Fracture distribution** | | | | | |
| Fracture frequency (fractures) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor SDev<br>Current: Low, NA, NA<br>Needed: Medium, Low, Low | Fracture density | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| **Parameter Category: Fracture orientation** | | | | | |
| Fracture orientation (fractures) | " | Goal: Mean SCor, SDev<br>Current: NA, NA, NA<br>Needed: Low, Low, Low | Fracture orientation | " | " |
| **Parameter Category: Unsaturated zone transmissive properties** | | | | | |
| Permeability, relative (fractures) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Low, Low, Low | Saturated hydraulic conductivity | Yucca Mountain, Surficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground water travel time | | | | (SCP 8.3.5.12) |
| Performance Measures: (Supporting parameters used in calculating performance parameters for ground water travel time.)<br>Boundary of repository-induced changes in effective fracture porosity<br>Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, vitric unit (primary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, zeolitized unit (primary reliance) | | | | | |
| Parameter Category: Unsaturated zone transmissive properties | | | | | |
| Permeability, relative (Rock mass) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Low | Unsaturated hydraulic conductivity | Yucca Mountain; Surficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| Permeability, relative (Rock matrix) | " | " | | | |
| Permeability, saturated (Fractures) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Medium | | | |
| Permeability, saturated (Rock mass) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: High, Low, Medium | | | |
| Permeability, saturated (Rock matrix) | " | Goal: Mean, SCor, SDev<br>Current: Low, NA, NA<br>Needed: High, High, High | | | |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.6** | Pre-waste-emplacement, ground water travel time | | | (SCP 8.3.5.12) | |
| Performance Measures: | (Supporting parameters used in calculating performance parameters for ground water travel time.)<br>Boundary of repository induced changes in effective fracture porosity<br>Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[a], Calico Hills non welded, vitric unit (primary reliance)<br>Ground water travel time[a], Calico Hills non welded, zeolitized unit (primary reliance) | | | | |
| | | Parameter Category: Unsaturated zone transmissive properties | | | |
| Porosity, effective (Fractures) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Low, Low, Low | | | |
| Porosity, effective (Rock mass) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: High, Medium, Medium | | | |
| Porosity, effective (Rock matrix) | " | " | | | |
| Fracture and matrix saturated permeability | Repository area; Subsurface | Goal: --<br>Current: --<br>Needed: -- | | | |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground water travel time | | | | (SCP 8.3.5.12) |
| Performance Measures: | Boundary of repository-induced changes in effective fracture porosity<br>(Supporting parameters used in calculating performance parameters for ground water travel time.)<br>Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, vitric unit (primary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, zeolitized unit (primary reliance) | | | | |
| Parameter Category: Unsaturated-zone transmissive properties | | | | | |
| Effective porosity and porosity of the fracture network, fault zones, rock mass, and matrix | Repository area; Subsurface | Goal: --<br>Current: --<br>Needed: -- | | | |
| Parameter Category: Unsaturated-zone storage properties | | | | | |
| Moisture-retention curve (Fractures) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Low, Low, Low | Porosity | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Moisture-retention curve (Rock mass) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Medium | " | " | 8.3.1.2.2.1.3 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|

**Issue 1.6** Pre-waste-emplacement, ground water travel time (SCP 8.3.5.12)

**Performance Measures:** (Supporting parameters used in calculating performance parameters for ground water travel time.)
Boundary of repository-induced changes in effective fracture porosity
Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)
Ground-water travel time[a], Calico Hills non-welded, vitric unit (primary reliance)
Ground-water travel time[a], Calico Hills non-welded, zeolitized unit (primary reliance)

**Parameter Category: Unsaturated zone storage properties**

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Moisture retention curve (Rock matrix) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: Low, NA, NA<br>Needed: Medium, Low, Medium | | | |
| Porosity, total (Fractures) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Medium | | | |
| Porosity, total (Rock matrix) | " | Goal: Mean, SCor<br>Current: NA, NA<br>Needed: High, High | | | |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground water travel time | | | | (SCP 8.3.5.12) |

Performance Measures: (Supporting parameters used in calculating performance parameters for ground water travel time.)
Boundary of repository-induced changes in effective fracture porosity
Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)
Ground-water travel time[a], Calico Hills non-welded, vitric unit (primary reliance)
Ground-water travel time[a], Calico Hills non-welded, zeolitized unit (primary reliance)

Parameter Category: Unsaturated-zone fluid potential

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Pressure head, matric potential (Fractures) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Low | Flow pathways | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Pressure head, matric potential (Rock matrix) | " | Goal: Mean, SCor, SDev<br>Current: Low, NA, NA<br>Needed: Medium, Low, Medium | Water potential | " | " |
| Saturation (and moisture content) values as a function of depth and lateral spatial location | Repository area; Subsurface | Goal: --<br>Current: --<br>Needed: -- | Flow pathways | " | 8.3.1.2.2.1.2 |
| Pressure head values as a function of depth and lateral spatial location | " | " | Water potential profiles | Yucca Mountain, Surficial soils and bedrock exposures | " |
| | | | Flow pathways | " | 8.3.1.2.2.1.3 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameter* | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground water travel time | | | | (SCP 8.3.5.12) |
| Performance Measures: | (Supporting parameters used in calculating performance parameters for ground water travel time.)<br>Boundary of repository-induced changes in effective fracture porosity<br>Ground-water travel time[e], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[e], Calico Hills non-welded, vitric unit (primary reliance)<br>Ground-water travel time[e], Calico Hills non welded, zeolitized unit (primary reliance) | | | | |
| | | Parameter Category: Unsaturated zone fluid potential | | | |
| | | | Water potential profiles | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| | | Parameter Category: Unsaturated zone moisture conditions | | | |
| Moisture content, volumetric (Fractures) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Low | Gravimetric water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and lithologic units | 8.3.1.2.2.1.1 |
| Moisture content, volumetric (Rock matrix) | " | Goal: Mean, SCor, SDev<br>Current: Low, NA, NA<br>Needed: High High, High | Surficial material water content | " | " |
| Saturation (Fractures) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: Medium, Low, Low | Water content profiles | Yucca Mountain; Surficial soils and bedrock exposures | " |

Table 7.2-1. Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground-water travel time | | | | (SCP 8.3.5.12) |
| Performance Measures: (Supporting parameters used in calculating performance parameters for ground water travel time.)<br>Boundary of repository-induced changes in effective fracture porosity<br>Ground-water travel time[a], Topopah Spring welded unit (secondary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, vitric unit (primary reliance)<br>Ground-water travel time[a], Calico Hills non-welded, zeolitized unit (primary reliance) | | | | | |
| Parameter Category: Unsaturated zone moisture conditions | | | | | |
| Saturation (Rock matrix) | Repository area; Unsaturated zone, each geohydrologic unit below repository | Goal: Mean, SCor, SDev<br>Current: Low, NA, NA<br>Needed: High, Medium, Medium | Water-content profiles | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| Moisture retention curves for wetting and draining | Repository area; Subsurface | Goal: --<br>Current: --<br>Needed: -- | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| Parameter Category: Unsaturated-zone fluid flux | | | | | |
| Flux (q)[b] | Controlled area; TSw[a] | Goal: <0.5 mm/yr[c,e]<br>Current: Low<br>Needed: Low | Evapotranspiration | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | 8.3.1.2.2.1.2 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

Issue 1.6 — Pre-waste-emplacement, ground water travel time (SCP 8.3.5.12)

Performance Measures: Ground-water travel time[e], Topopah Spring welded unit (secondary reliance)
Ground-water travel time[e], Calico Hills non-welded, vitric unit (primary reliance)
Ground-water travel time[e], Calico Hills non-welded, zeolitized unit (primary reliance)
(Supporting parameters used in calculating performance parameters for ground water travel time.)
Boundary of repository-induced changes in effective fracture porosity

Parameter Category: Unsaturated zone fluid flux

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Distance along flow paths | Controlled area; TSw | Goal: >10 m (100%)<br>Current: Medium<br>Needed: Low | Infiltration rates, net | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| Flux (q) | Controlled area; CHnv | Goal: <0.5 mm/yr<br>Current: Low<br>Needed: High | Infiltration rates, surface | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | " |
| Distance along flow paths | " | Goal: >2.5 m (100%), >25 m (80%)<br>Current: Low[f], Low[f]<br>Needed: High, Medium | Flow velocity | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| Flux (q) | Controlled area, CHnz | Goal. <0.5 mm/yr<br>Current: Medium<br>Needed: High | Maximum artificial infiltration rate | " | " |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.6 | Pre-waste-emplacement, ground water travel time | | | | (SCP 8.3.5.12) |
| Performance Measures: Ground-water travel time[e], Calico Hills non-welded, zeolitized unit (primary reliance) (Supporting parameters used in calculating performance parameters for ground water travel time.) Boundary of repository induced changes in effective fracture porosity | | | | | |
| | | Parameter Category: Unsaturated zone fluid flux | | | |
| Distance along flow paths | Controlled area; CHnz | Goal: >2.5 m (100%), >25 m (80%)<br>Current: Low[f], Low[f]<br>Needed: High, Medium | Maximum infiltration rate | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| Flux, percolation rate (Fractures) | Repository area; Unsaturated zone, TSw2, repository level | Goal: Mean, SCor, SDev<br>Current: NA, NA, Medium<br>Needed: Medium, Low, Low | Saturated hydraulic infiltration rate | " | " |
| Flux, percolation rate (Rock matrix) | " | Goal: Mean, SCor, SDev<br>Current: NA, NA, NA<br>Needed: High, Medium, Medium | | | |
| Ground-water percolation flux at the top of TSw2 (portion of Topopah Spring welded unit proposed for repository unit) | Repository area; Subsurface | Goal: --<br>Current: --<br>Needed: -- | | | |

Table 7.2-1. Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.10** | Waste package characteristics (postclosure) | | | (SCP 8.3.4.2) | |
| Performance Measures: Rock-induced load on waste package<br>Quantity of liquid water that can contact the container | | | | | |
| | | Parameter Category: Fracture distribution | | | |
| Fracture orientation and density: average spacing within each borehole | Repository area; Repository block: TSw2 | Current:<br>Needed: High | Fracture density | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Fracture orientation and density: set identification | " | " | | | |
| For Topopah Spring Tuff at repository horizon (TSw2)[b]: Fracture spacing | " | Current:<br>Needed: Medium | | | |
| | | Parameter Category: Fracture orientation | | | |
| Fracture orientation and density: distribution of orientation | " | Current:<br>Needed: High | Fracture orientation | Yucca Mountain, Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.10** | **Waste package characteristics (postclosure)** | | | | **(SCP 8.3.4.2)** |
| **Performance Measures: Quantity of liquid water that can contact the container** | | | | | |
| | | **Parameter Category: Unsaturated zone transmissive properties** | | | |
| Single-phase fluid flow; relative permeability (water quantity) | Waste package near-field environment; 1.5.2 | Goal: +/- 20%<br>Current: --<br>Needed: -- | Saturated hydraulic conductivity | Yucca Mountain; Surficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| Single-phase fluid flow; fracture permeability (water quantity) | " | " | Unsaturated hydraulic conductivity | " | " |
| Two-phase fluid flow; relative permeability (water quantity) | " | " | | | |
| Two-phase fluid flow; fracture permeability (water quantity) | " | " | | | |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.10** | Waste package characteristics (postclosure) | | | | (SCP 8.3.4.2) |
| Performance Measures: Quantity of liquid water that can contact the container | | | | | |
| | | Parameter Category: Unsaturated zone moisture conditions | | | |
| Single-phase fluid flow; degree of saturation (water quantity) | Waste package near field environment; TSw2 | Goal: +/- 50%<br>Current: --<br>Needed: - | Gravimetric water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Two-phase fluid flow; degree of saturation (water quantity) | " | " | Surficial material water content | " | " |
| | | | Water content profiles | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | " | " | 8.3.1.2.2.1.2 |
| | | | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2-1. Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.10** | Waste package characteristics (postclosure) | | | | (SCP 8.3.4.2) |
| Performance Measures: Quantity of liquid water that can contact the container | | | | | |
| | | Parameter Category: Unsaturated zone fluid flow | | | |
| Water quantity: single-phase fluid flow | Repository area; Repository block: TSw2 | Current: Needed: High | Evapotranspiration | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | 8.3.1.2.2.1.2 |
| Water quantity: two-phase fluid flow | " | " | Infiltration rates, net | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | Infiltration rates, surface | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | " |
| | | | Flow velocity | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| | | | Maximum artificial infiltration rate | " | " |

Table 7.2-1. Design and performance issues and parameters suggested by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.10** Waste package characteristics (postclosure) (SCP 8.3.4.2) | | | | | |
| **Performance Measures:** | | | | | |
| **Parameter Category: Unsaturated zone fluid flow** | | | | | |
| | | | Maximum infiltration rate | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.3 |
| | | | Saturated hydraulic infiltration rate | " | " |
| **Issue 1.11** Characteristics and configurations of repository and engineered barriers (postclosure) (SCP 8.3.2.2) | | | | | |
| **Performance Measures:** Potential for significant displacement (see Issue 1.1); Stress, deformation, factor of safety, and potential rock fall; Extent of change in saturation and water chemistry | | | | | |
| **Parameter Category: Fracture distribution** | | | | | |
| Joint abundance (TSw2) | Primary area and extensions; TSw2 | Goal: See SCP Table 6.15[5]<br>Current: Low<br>Needed: Medium | Fracture density | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.11** | Characteristics and configurations of repository and engineered barriers (postclosure) | | | | (SCP 8.3.2.2) |
| Performance Measures: | Stress, deformation, factor of safety, and potential rock fall<br>Potential for significant displacement (see Issue 1.1)<br>Extent of change in saturation and water chemistry | | | | |
| **Parameter Category: Fracture distribution** | | | | | |
| Joint abundance (TSw1, TSw3, and CHn1) | Primary area and extensions; TSw1, TSw3, CHn1 | Goal: See SCP Table 8-15[a]<br>Current: Low<br>Needed: Low | | | |
| **Parameter Category: Fracture orientation** | | | | | |
| Joint spatial orientation (TSw2) | Primary area and extensions; TSw2 | Goal: See SCP Table 8-15[a]<br>Current: Low<br>Needed: Medium | Fracture orientation | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Joint spatial orientation (TSw1, TSw3, and CHn1) | Primary area and extensions; TSw1, TSw3, CHn1 | Goal: See SCP Table 8-15[a]<br>Current: Low<br>Needed: Low | | | |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.11** | Characteristics and configurations of repository and engineered barriers (postclosure) | | | | (SCP 8.3.2.2) |
| Performance Measures: Extent of change in saturation and water chemistry | | | | | |
| Parameter Category: Unsaturated zone moisture conditions | | | | | |
| Saturation (During development around the excavations) | Primary area and extensions; 1Sw2 | Goal: <90%<br>Current: Low<br>Needed: High | Gravimetric water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Surficial material water content | " | " |
| | | | Water-content profiles | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | " | " | 8.3.1.2.2.1.2 |
| | | | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2-1. Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.12 | Seal characteristics | | | | (SCP 8.3.3.2) |
| Performance Measures: Quantity of water<br>Quantity of water<br>Drainage capacity | | | | | |
| **Parameter Category: Rock-unit lateral and vertical variability** | | | | | |
| Gradation of alluvium | Shaft locations, mostly within 15 m from shaft & borehole locations; Near surface | Goal: Determination through standard sieving analyses<br>Current: Low<br>Needed: Not applicable | Bedrock outcrop | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Soil and alluvium thickness | " | " |
| | | | Texture | " | " |
| **Parameter Category: Fracture distribution** | | | | | |
| Fracture characteristics | Repository area; TCw | Goal: <20 fractures/m<br>Current: Low<br>Needed: High | Fracture density | " | " |
| " | PTn | Goal: <10 fractures/m<br>Current: Low<br>Needed: High | | | |

Table 7.2.1 Design and performance issues and parameters suggested by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 1.12** | **Seal characteristics** | | | | (SCP 8.3.3.2) |
| **Performance Measures:** Quantity of water<br>Drainage capacity | | | | | |
| | | **Parameter Category: Surface-water flood and runoff characteristics** | | | |
| Quantity of water due to surface flooding events; 100 and 500 yr flood and probable maximum flood, including area of inundation and debris load of flows | Shaft, ramp, and borehole locations; Land surface | Goal: Inundation maps with elevation of inundated area to within +/- 2 m<br>Current: Low<br>Needed: Medium | Correlation of surficial materials properties with spectral responses | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| " | " | Goal: Determine topography of drainage area using 2 m contours<br>Current: Medium<br>Needed: Medium | Infiltration runoff map units | " | " |
| Magnitude of water entering shafts | ES 1, ES 2, MH and EE shafts; | Goal: <150 $m^3$/yr per shaft considering anticipated processes<br>Current: Low<br>Needed: Low | Rainfall runoff infiltration relations | Yucca Mountain, Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1.3 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.12 | Seal characteristics | | | | (SCP 8.3.3.2) |
| Performance Measures: Quantity of water | | | | | |
| | | Parameter Category: Unsaturated zone transmissive properties | | | |
| Saturated hydraulic conductivity of alluvium | Within 75 m of shaft location; Near surface | Goal: 1 x $10^{5}$ to 1 x $10^{2}$ cm/s<br>Current: Low<br>Needed: Medium | Saturated hydraulic conductivity | Yucca Mountain; Surficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| Saturated bulk-rock hydraulic conductivity of Tiva Canyon Member | Vicinity of shaft locations; TCw | " | Unsaturated hydraulic conductivity | " | " |
| Extent and hydraulic conductivity of modified permeability zone (MPZ) | Vicinity of shaft locations; TCw; TSw2 | Goal: Less than or equal to 60 times the undisturbed, rock mass saturated hydraulic conductivity, averaged over one radius from the wall of the shaft<br>Current: Low<br>Needed: Medium | | | |
| Unsaturated hydraulic, matrix properties | Vicinity of shaft locations; TSw2 | Goal: 1 x $10^{8}$ to 1 x $10^{15}$ m/s<br>Current: Low<br>Needed: Medium | | | |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 1.12 | Seal characteristics | | | | (SCP 8.3.3.2) |
| Performance Measures: Quantity of water | | | | | |
| Parameter Category: Unsaturated zone moisture conditions | | | | | |
| Continuous saturation profile of alluvium to bedrock-alluvium interface | Shaft and borehole locations; Near surface | Goal: +/- 10% of natural saturation every meter<br>Current: Low<br>Needed: Medium | Gravimetric water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Surficial material water content | " | " |
| | | | Water content profiles | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | " | " | 8.3.1.2.2.1.2 |
| | | | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 2.1** Expected radiation dose received by public in restricted and unrestricted areas (SCP 8.3.5.3) | | | | | |
| **Performance Measures:** Radionuclides concentrations in environmental media and individual doses | | | | | |
| **Parameter Category: Surface water flood and runoff characteristics** | | | | | |
| Volumetric flow of surface water to water bodies | 80 km radius; Land surface | Goal: Little or no surface runoff<br>Current: Medium<br>Needed: Medium | Correlation of surficial materials properties with spectral responses | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Infiltration runoff map units | " | " |
| | | | Rainfall runoff infiltration relations | Yucca Mountain, Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1.3 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 2.2** | Worker radiological safety under normal operating conditions | | | | (SCP 8.3.5.4) |
| Performance Measures: Effective attenuation of direct radiation by host rock | | | | | |
| | | Parameter Category: Unsaturated zone moisture conditions | | | |
| Water content of host rock | TSw2 | Goal: Tentative goal is to have further measurements of this parameter verify the range of expected values listed here<br>Current: Medium<br>Needed: High | Gravimetric water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Surficial material water content | " | " |
| | | | Water content profiles | Yucca Mountain, Surficial soils and bedrock exposures | " |
| | | | " | " | 8.3.1.2.2.1.2 |
| | | | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameter | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 2.3** | **Exposures to public (credible accidents)** | | | | **(SCP 8.3.5.5)** |
| **Performance Measures:** Consequences of credible site-related accidents; Long-term dispersion, diffusion, and bioaccummulation characteristics of the site | | | | | |
| **Parameter Category: Surface-water flood and runoff characteristics** | | | | | |
| Frequency and magnitudes of repository surface flooding | Repository facilities; land surface | Goal: PMF (Probable maximum flood)<br>Current: Medium<br>Needed: High | Correlation of surficial materials properties with spectral responses | Yucca Mountain; surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Volumetric flow of surface water to water bodies | 80-km radius; land surface | Goal: Little or no surface runoff<br>Current: Medium<br>Needed: Medium | Infiltration runoff map units | " | " |
| | | | Rainfall runoff infiltration relations | Yucca Mountain; surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1.3 |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 2.7 | Characteristics and configurations of the repository (preclosure) | | | | (SCP 8.3.2.3) |
| Performance Measures: | Ability to detect radioactive materials in repository effluent streams<br>Decontamination factor<br>Moderating materials in or around emplaced waste | | | | |
| | | Parameter Category: Surface water flood and runoff characteristics | | | |
| Volumetric flow of surface water to water bodies (80 km radius) | Area within 80 km of site, Land surface | Goal: Little or no surface runoff<br>Current: Medium<br>Needed: Medium | Correlation of surficial materials properties with spectral responses | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Repository surface flooding (At facility) | Repository area; Land surface | Goal: PMF[a]<br>Current: Medium<br>Needed: High | Infiltration runoff map units | " | " |
| | | | Rainfall runoff infiltration relations | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1 |
| | | Parameter Category: Unsaturated zone moisture conditions | | | |
| Water content of host rock as a function of temperature and time (TSw2 unit) | Primary area and extensions; TSw2 | Goal: See footnote (d)<br>Current: Medium<br>Needed: High | Gravimetric water content | Yucca Mountain, Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 2.7 | Characteristics and configurations of the repository (preclosure) | | | | (SCP 8.3.2.3) |
| Performance Measures: | | | | | |
| | | | | | |
| Parameter Category: Unsaturated zone moisture conditions | | | | | |
| | | | Surficial material water content | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Water content profiles | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | " | " | 8.3.1.2.2.1.2 |
| | | | " | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 4.4 | Repository construction, operation, closure, and decommissioning technologies | | | | (SCP 8.3.2.5) |
| Performance Measures: Usable openings of required size<br>Soil and rock conditions<br>Compliance with 10 CFR 60.133 (g)<br>Removal rate equal to rate of inflow | | | | | |
| | | Parameter Category: Fracture distribution | | | |
| Number of joint sets | Primary area; Repository block, TSw2 | Goal: TSw2, 2 - 3 sets<br>Current: Medium<br>Needed: High | Fracture density | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| Fracture frequency and spacing | " | Goal: TSw2, 20 - 40 per $m^3$<br>Current: Medium<br>Needed: Medium | | | |
| | | Parameter Category: Fracture orientation | | | |
| Joint orientation | " | Goal: TSw2, identify joint sets and orientation<br>Current: Medium<br>Needed: Medium | Fracture orientation | Yucca Mountain, Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |

Table 7.2.1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| **Issue 4.4** | Repository construction, operation, closure, and decommissioning technologies | | | | (SCP 8.3.2.5) |
| Performance Measures: Soil and rock conditions<br>Compliance with 10 CFR 60.133 (g)<br>Removal rate equal to rate of inflow | | | | | |
| | | Parameter Category: Surface water flood and runoff characteristics | | | |
| Favorable infiltration/runoff ratio | Yucca Mountain, vicinity of surface facilities; Land surface | Goal: See SCP Section 8.3.1.2 (geohydrology)<br>Current: Low<br>Needed: High | Correlation of surficial materials properties with spectral responses | Yucca Mountain; Surficial soils and rocks, hydrogeologic and bedrock units | 8.3.1.2.2.1.1 |
| | | | Infiltration runoff map units | " | " |
| | | | Rainfall runoff infiltration relations | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.2 |
| | | | " | " | 8.3.1.2.2.1.3 |
| | | Parameter Category, Unsaturated zone transmissive properties | | | |
| Permeability of disturbed rock | Primary area; Underground facility | Goal: Permeability of rock affected by mining operations (blasting)<br>Current: Low<br>Needed: Low | Saturated hydraulic conductivity | Yucca Mountain, Surficial soils and bedrock exposures, hydrogeologic and bedrock units | " |

Table 7.2-1. Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 4.4 | Repository construction, operation, closure, and decommissioning technologies | | | | (SCP 8.3.2.5) |
| Performance Measures: Removal rate equal to rate of inflow | | | | | |
| | | Parameter Category: Unsaturated-zone transmissive properties | | | |
| | | | Unsaturated hydraulic conductivity | Yucca Mountain; Surficial soils and bedrock exposures, hydrogeologic and bedrock units | 8.3.1.2.2.1.3 |
| | | Parameter Category: Unsaturated-zone fluid flux | | | |
| Natural water inflow | Repository facilities; | Goal: Actual inflow rate to accuracy of +/- 10 gpm<br><br>Current: Low<br>Needed: Medium | Evapotranspiration | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | 8.3.1.2.2.1.2 |
| | | | Infiltration rates, net | Yucca Mountain; Surficial soils and bedrock exposures | " |
| | | | Infiltration rates, surface | Yucca Mountain; Surficial soils and bedrock exposures, surficial hydrogeologic and bedrock units | " |

Table 7.2-1 Design and performance issues and parameters supported by results of this study

| Design and Performance Parameters | Parameter Location | Parameter Goal and Confidence (Current and Needed) | Site Parameters | Parameter Location | Site Activity |
|---|---|---|---|---|---|
| Issue 4.4 | Repository construction, operation, closure, and decommissioning technologies | | | (SCP 8.3.2.5) | |
| Performance Measures: | | | | | |
| Parameter Category: Unsaturated zone fluid flux | | | | | |
| | | | Flow velocity | Yucca Mountain; Surficial soils and bedrock exposures | 8.3.1.2.2.1.5 |
| | | | Maximum artificial infiltration rate | " | " |
| | | | Maximum infiltration rate | " | " |
| | | | Saturated hydraulic infiltration rate | " | " |

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