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Chapter 3

HYDROLOGY

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Chapter 3

HYDROLOGY

This chapter summarizes present knowledge of the regional and site hydrologic systems. The purpose of the information presented is to (1) describe the hydrology based on available literature and preliminary site-exploration activities that have been or are being performed and (2) provide information to be used to develop the hydrologic aspects of the planned site characterization program.

INTRODUCTION

An understanding of the hydrologic regime is required for many of the issues in the Nevada Nuclear Waste Storage Investigations (NNWSI) Project Issues Hierarchy (Section 8.2). In particular, the nine Performance Issues (1.1 through 1.9) of Key Issue 1 (related to the postclosure environment); the Characterization Programs 8.3.1.2 (geohydrology), 8.3.1.3 (geochemistry), and 8.3.1.9 (water resources); the Performance Issue (4.1) of Key Issue 4 (preclosure); and the Characterization Program 8.3.1.16 (hydrology) all pertain directly to hydrology. In addition, other programs are indirectly related to hydrology, (e.g., Programs 8.3.1.5, 8.3.1.6, and 8.3.1.8 question the effects that climatic change, erosional processes, and tectonic processes exert on the hydrologic characteristics at the site). Furthermore, issues related to design (both in the preclosure and postclosure time frames) require a knowledge of the emplacement environment, a major component of which is moisture. Therefore, an understanding of the hydrologic system in and around Yucca Mountain is paramount to satisfying many of the issues in the issues hierarchy.

One of the primary advantages of the proposed Yucca Mountain repository site is that it is intended to be located in the unsaturated zone, approximately 300 m above the saturated zone. This chapter discusses in detail the present understanding of hydrologic conditions within the unsaturated zone, as well as conditions in the saturated zone and in the surface hydrologic systems; the last two act as boundaries to the unsaturated zone.

For convenience in describing the hydrologic regime, two types of study areas are defined in this chapter: (1) a hydrographic study area (Figure 3-1) that delineates the regional surface water system that encompasses Yucca Mountain and (2) a hydrogeologic study area (Figure 3-2), the boundaries of which approximate the regional ground-water flow system surrounding Yucca Mountain. These study areas represent the areas from which published data were compiled to describe the hydrology of the region and site; additional investigations are planned for parts of these study areas, as described in Section 8.3.1.2.

The hydrographic study area is composed of eight smaller hydrographic areas as described by Waddell et al. (1984) (Figure 3-1). Yucca Mountain lies on the boundary of the Crater Flat and Fortymile Canyon-Jackass Flats hydrographic areas. Detailed discussions of the surface-water system within

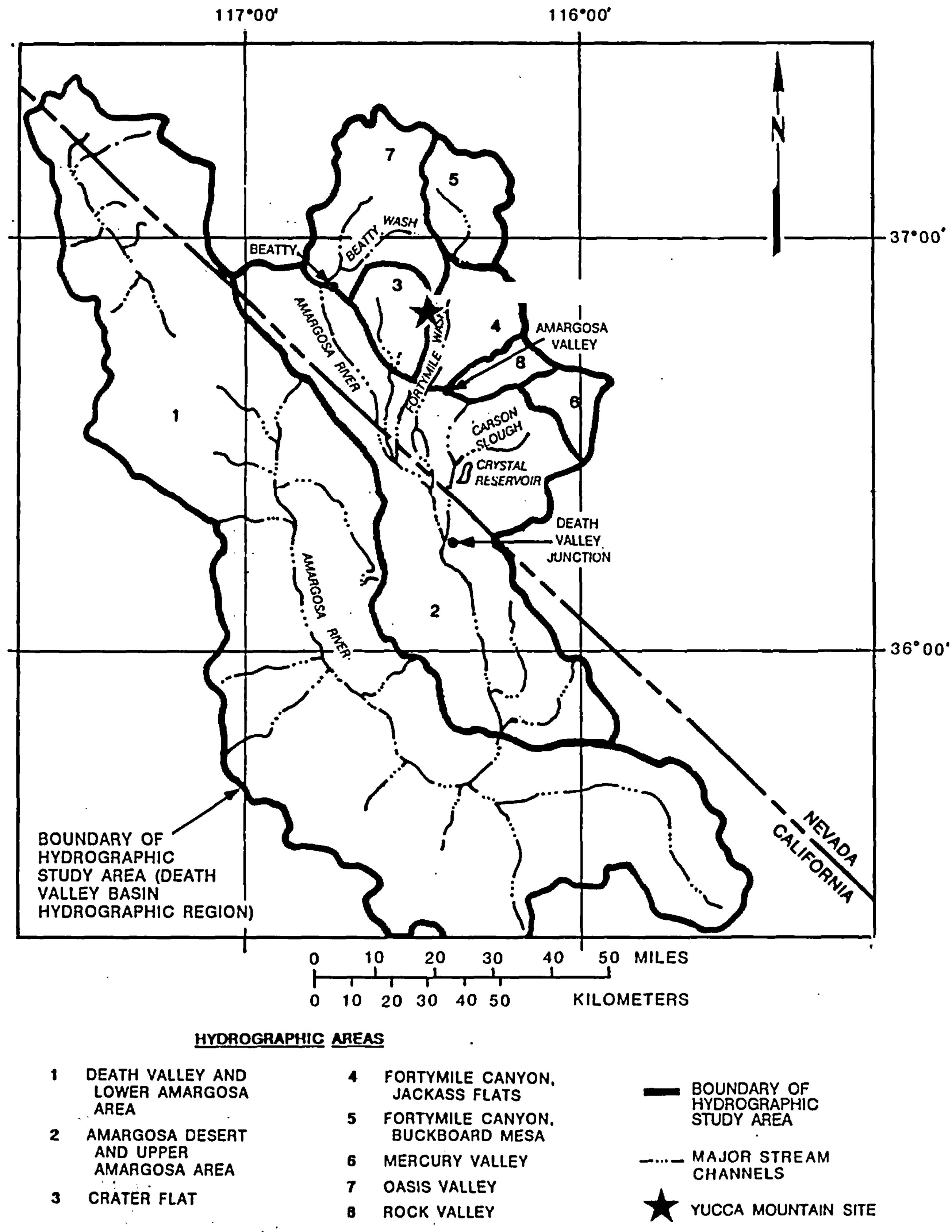
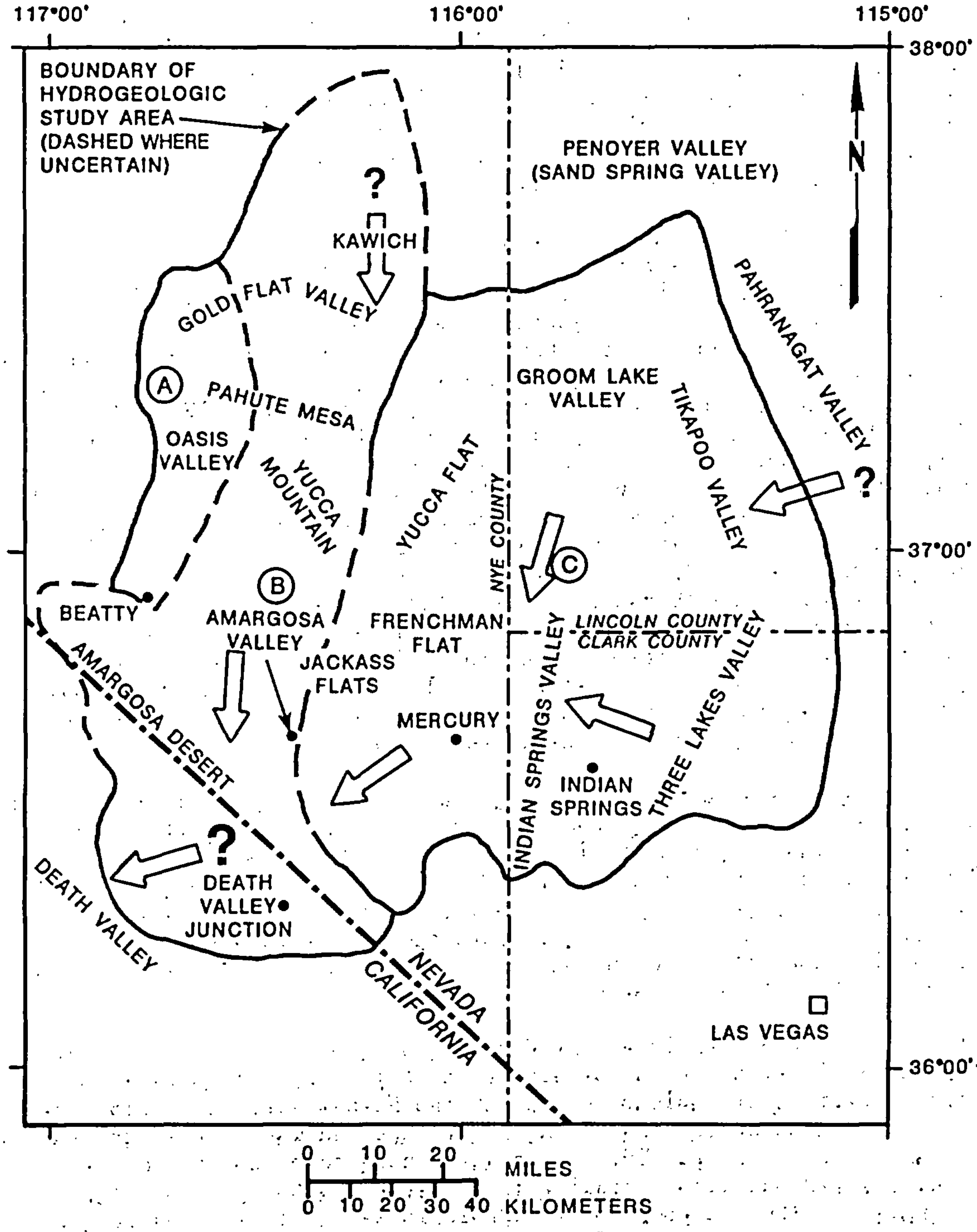


Figure 3-1. Hydrographic study area, showing the eight hydrographic areas and major stream channels. Modified from Waddell, et al. (1984).



GENERAL DIRECTION OF REGIONAL GROUND-WATER FLOW (QUESTION MARK INDICATES UNCERTAINTY)

A. OASIS VALLEY SUBBASIN
B. ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN
C. ASH MEADOWS SUBBASIN

Figure 3-2. Hydrogeologic study area, showing three ground-water subbasins. Modified from Rush (1970), Blankennagel and Weir (1973), Winograd and Thordarson (1975), Dudley and Larsen (1976), Waddell (1982), and Waddell, et al. (1984).

the hydrographic study area are presented in Section 3.1 (description of surface hydrology), 3.2 (floods), 3.3 (locations and distances to points of surface-water use), and 3.4 (chemical composition of adjacent watercourses). As these sections discuss, the occurrence of surface-water bodies is extremely limited in the vicinity of Yucca Mountain; their primary importance is in their relationship to the ground-water system, as discussed in Section 3.5 (points of ground-water discharge).

The hydrogeologic study area (Figure 3-2) consists of three ground-water subbasins that together form a part of the Death Valley ground-water basin (Waddell et al., 1984). These subbasins are the Oasis Valley subbasin, Alkali Flat-Furnace Creek Ranch subbasin, and the Ash Meadows subbasin. The division into and the approximate boundaries of these ground-water subbasins have been estimated from potentiometric levels, geologic controls of subsurface flow, discharge areas, and inferred flow paths (Rush, 1970; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Waddell, 1982; Waddell et al., 1984). In some areas, the boundaries are uncertain due to the lack of potentiometric data, the complexity of geologic structures, or the occurrence of interbasin flow of ground water through the lower carbonate aquifer (Winograd and Thordarson, 1975). Regional flow paths in the hydrogeologic study area vary in direction from southerly to southwesterly (Winograd and Thordarson, 1975; Waddell, 1982). Detailed discussions of the regional hydrogeology and regional flow systems are included in Sections 3.6 and 3.7. Detailed discussions of the site (Yucca Mountain) hydrogeology are included in Section 3.9. The discussions include aquifer-hydraulics information, water-balance calculations, and water-chemistry data for both the saturated and the unsaturated zones.

Most of the information on the regional hydrology is available in published reports from general ground-water studies made during the 1960s and 1970s by the Nevada Department of Conservation and Natural Resources or by the Department in cooperation with the U.S. Geological Survey (USGS). The studies were used principally for general water-resource appraisals of parts of Nevada. A few studies of surface hydrology were also made, but because the region is generally arid and because streamflow is essentially ephemeral, very few data have been collected.

In 1957 the U.S. Atomic Energy Commission (later the Energy Research and Development Administration and presently the Department of Energy) began underground testing of nuclear devices at the Nevada Test Site (NTS), and therefore needed an evaluation of the occurrence and movement of ground water within and adjacent to the NTS. There was a need to determine both the potential for radionuclide contamination of ground water and location of water supplies. Thus, a program of hydrologic and geologic studies was established between the Atomic Energy Commission and the USGS and has continued since the late 1950s to the present. In a paper published in 1975, Winograd and Thordarson (1975) summarized the current understanding of the regional hydrogeology and flow systems within the hydrogeologic study area. This report is the basis for the more recent hydrologic studies, such as a regional ground-water flow modeling effort by Waddell (1982). Regional ground-water studies for the NNWSI Project have continued because they provide an understanding of the ground-water flow system in the vicinity of Yucca Mountain. Furthermore, regional studies provide a basis for evaluating future changes in climate and hydrology. Such possible future effects may be important to isolation of waste at Yucca Mountain.

In general, hydrogeologic data for the region are believed to be adequate for regional quantitative ground-water flow modeling, although there remain some hydrologic features that are not completely understood for the purposes of site characterization. Where it is important to resolve such questions (such as the potential for recharge near Fortymile Wash), plans have been developed for additional field studies as described in Section 8.3.1.2.1. Various hypotheses about the ground-water flow systems and probable present and future fluxes are continuing to be evaluated to improve general understanding and to determine probable error bounds for calculated quantities such as ground-water velocities and future water levels. These hypotheses are discussed in Sections 3.6, 3.7, and 3.9.

Most of the hydrologic information about the Yucca Mountain site has been obtained from studies conducted since 1978. During the first few years of these studies, the emphasis was on describing the hydrogeology of the saturated zone. As additional data became available, consideration was given to locating the repository within the unsaturated zone. The unsaturated zone at Yucca Mountain is thick (500 to 750 m at the proposed repository) and offers several possible advantages over the saturated zone, including longer ground-water travel times from the repository to the accessible environment, the existence of a zeolitic tuff along the flow path that may retard radionuclide transport, and the avoidance of difficulties associated with constructing and operating a repository within the saturated zone. Because of the recent shift of investigative emphasis to the unsaturated zone and the lack of previous investigations of thick unsaturated zones, less is known about it than about the saturated zone. However, present and planned studies are designed to develop a comprehensive understanding of the hydrology of the unsaturated zone at Yucca Mountain (Section 8.3.1.2.2).

Beginning in 1981, hydrologic test holes, some as deep as 1.8 km, were drilled into the saturated zone at Yucca Mountain. The holes were logged to determine lithology and stratigraphy of the rocks penetrated and tested to determine such hydrologic parameters as depth to water, total water yield, water yield as a function of stratigraphic horizon, hydraulic conductivity, transmissivity, and water chemistry, including apparent carbon-14 ages of some of the waters. The upper kilometer or more of the saturated zone penetrated by the wells consists of extensively fractured volcanic tuffs that appear to derive most of their permeability from the fractures, rather than from the porosity of a granular matrix.

Hydraulic tests of the saturated zone in these drillholes were evaluated mostly by porous media methods. Depending on the scale of study, such methods may or may not be applicable for evaluating the results of aquifer tests conducted in fractured media. Investigations of the hydraulic behavior of fractured-rock aquifers are still considered developmental; indeed, most of the studies have been initiated in direct response to the needs of this and other radioactive waste repository projects. Three approaches are commonly taken: (1) the continuum approach in which the aquifer is modeled, both with respect to transport of water and solutes, as an equivalent porous medium; (2) the dual porosity approach in which the rock matrix and fractures are treated as coupled flow systems of highly differing properties; and

(3) the discrete fracture approach in which flow through a regular geometric network of parallel-plate fractures is simulated using fluid-dynamics equations. Newer approaches involve the application of near-field stochastic analyses to predict far-field hydraulic and transport properties. Alternative approaches will be examined as the project develops and as the state of the modeling art is refined (Section 3.9).

In addition, multiple-well tests, some of which involve tagging ground water with tracers to evaluate the tests, will be conducted within the saturated zone. The purpose of these tests is to determine the nature and extent of the permeability contributed by fractures and to determine effective porosity.

Beginning in 1983, test holes were drilled to depths greater than 300 m within the unsaturated zone. The purposes of these boreholes were to obtain rock samples for the determination of hydrologic properties and to monitor ambient water saturation, potential, and flux in rocks above, below, and within the horizon proposed for the repository. Rock samples have been tested to determine effective porosities, ambient saturations and matric potentials, saturated matrix hydraulic conductivities, and water retention characteristics. Ambient water potentials have been monitored in one test well since 1983. The data from the rock samples show a wide variation in hydrologic property values between the various hydrogeologic units within the unsaturated zone. The in situ water potential data show considerable variability; however, the data are consistent with the supposition that the hydrogeologic units are vertically homogeneous and that steady-state vertical moisture flow occurs under unit vertical hydraulic gradients. The mechanisms of moisture flow and storage (as liquid water, water vapor, or both) at any location within the system depend largely upon the amount of water entering the system as net infiltration. The actual rate and distribution of net infiltration across the unsaturated zone is not known, although likely upper bounds have been established. Because little is known about ground-water occurrence and movement within deep zones of unsaturated, fractured tuffs, an extensive program of field investigations and theoretically based studies is planned to provide a comprehensive understanding of the hydrology of the unsaturated zone at Yucca Mountain (Section 8.3.1.2.2).

Uncertainty associated with the data presented in Chapter 3 is primarily related to the lack of a sufficient number of samples or tests for statistical reliability and also to measurement errors that are inherent in the investigations. As with all scientific investigations, however, certain levels of uncertainty associated with the data are generally acceptable. The level of uncertainty that can be considered acceptable is determined by the level to which the parameter must be known based on the sensitivity of the system to that parameter.

The evaluation of uncertainty associated with measured parameters has been addressed, where possible, by planning testing and sampling programs that are structured so that experimental uncertainty and sampling uncertainty are independently or jointly characterized. These programs for site characterization are described in Section 8.3.1.2. Specific levels and types of existing uncertainties or data needs are discussed throughout Chapter 3.

In very general terms, the regional hydrology and hydrogeology are fairly well understood and their levels of uncertainty are relatively low. However, the unsaturated zone at the site has only recently come under investigation and, therefore, has produced a relatively meager data base. There is also a considerable uncertainty regarding the degree to which the limited data base represents the actual range of conditions at the site.

Examples of uncertainties associated with the hydrologic and hydrogeologic data presented in Chapter 3 are as follows:

1. The quantity of streamflow and flood records are insufficient for accurate predictions of future magnitudes and recurrence intervals because of the relatively short period of record.

2. Several portions of the regional flow system are uncertain, including quantities of evapotranspiration in the Amargosa Desert, vertical components of flow within the saturated zone, and the nature of hydrologic boundary conditions at the site (to be provided by regional models). These factors are insufficiently known due to the lack of data collected to this point.

3. Uncertainties exist concerning the site saturated flow system. Included among these are the reasons for the existence of a locally steep hydraulic gradient (upgradient from the site) and the associated difficulties related to characterization of saturated-zone flux within and around this zone. These uncertainties arise from an insufficient data base for proper quantification of ground-water behavior in the area.

4. Knowledge of the nature and quantities of present and future infiltration is insufficient for use in unsaturated-zone flux or travel-time calculations, due to the lack of existing infiltration measurements and the lack of hydrologic data that could be used to estimate infiltration characteristics.

5. Because of the limited number of studies available, projections of future hydrologic conditions are difficult to make based on paleoclimatic and paleohydrologic data.

6. The quantity of water chemistry data, especially from the unsaturated zone, is not sufficient for verification of conceptual-flow models.

7. Ambient hydrologic conditions within the fractured rocks of the unsaturated zone are not well known because of the very limited number of tests and measurements performed to date.

8. Knowledge of the behavior of water and gases within the fractured terrane at Yucca Mountain and the interaction of the matrix and fracture systems are not sufficient due to the limited amount of data collected to this point and the limited amount of relevant information available in the open literature.

9. The conceptual model of ground-water flow through the unsaturated zone at the site has not been developed to a high confidence level as yet because of the limitations of the supporting data.

These and other areas of uncertainty will be significantly reduced through further data collection and through the application of multiple approaches that may produce corroborative results. These programs will be carried out during site characterization and are described in Section 8.3.1.2.

3.1 DESCRIPTION OF SURFACE HYDROLOGY

Characterization of surface hydrology is required to provide baseline data necessary to resolve several issues. Knowledge gained through the surface hydrology studies will be used to (1) evaluate the potential for erosion in the site area and any hazards that this may cause, (2) evaluate the potential for floods and the potential hazards to the surface facilities due to floods (Section 3.2), and (3) help evaluate the amount of infiltration and establish the relationship between surface runoff and ground-water recharge that occurs in the study area.

The hydrographic study area (Figure 3-1) is the same as the Death Valley Basin Hydrographic Region of California and Nevada, as defined by Rush (1968) and the USGS (1978). This study area consists of eight hydrographic areas. The boundary lines of the eight hydrographic areas within the hydrographic study area are drawn principally along topographic divides. These hydrographic areas serve as the basic morphologic unit of the surface-water hydrologic system. A listing of these areas is shown in Table 3-1.

The general configuration of surface drainage of the hydrographic areas is shown in Figure 3-1. The Yucca Mountain site proposed for waste disposal lies on the boundary between the Crater Flat and Fortymile Canyon-Jackass Flats hydrographic areas (Figure 3-1).

The eastern slopes of Yucca Mountain drain to Fortymile Wash and the northern slopes drain to Beatty Wash; these washes are major tributaries to the Amargosa River. The southern and western slopes of Yucca Mountain drain to the Amargosa River through a smaller unnamed drainage system.

There are no perennial streams in or near the Yucca Mountain area. However, the many ephemeral stream channels, including the large drainage systems of Fortymile Wash and the Amargosa River, flow following significant regional or local storms. Although the region that includes Yucca Mountain has a generally arid to semiarid climate that includes high annual average potential evaporation (about 1,500 to 1,700 mm/yr; Kohler et al., 1959), low average annual precipitation (about 150 mm; Quiring, 1983), and infrequent storms (Section 5.1.1.6), surface runoff does occur. Runoff results from regional storms that occur most commonly in autumn, winter, and spring, and from localized thunderstorms that occur mostly during the summer. Rugged relief, abundant bedrock exposed at the land surface, and sparse vegetal cover promote runoff, particularly during intense rainstorms. The annual precipitation pattern usually follows a bimodal distribution, with greatest

Table 3-1. Hydrographic areas in the hydrographic study area

Area number on Figure 3-1	Hydrographic area	State[a,b]	Approximate area (mi^2)	Approximate area (km^2)
1	Death Valley and Lower Amargosa area	Nevada California	344 5,019	891 13,000
2	Amargosa Desert and Upper Amargosa area	Nevada California	896 1,122	2,321 2,906
3	Crater Flat	Nevada	182	471
4	Fortymile Canyon, Jackass Flat	Nevada	279	723
5	Fortymile Canyon, Buckboard Mesa	Nevada	240	622
6	Mercury Valley	Nevada	110	285
7	Oasis Valley	Nevada	460	1,191
8	Rock Valley	Nevada	82	212

[a]Data for Nevada modified from Rush (1968).
[b]Data for California from U.S. Geological Survey (1978).

average amounts occurring during the winter storms and less during the summer (Quiring, 1983). Although runoff can result from severe winter storms, the scanty data available for the region suggests that greatest runoff magnitudes commonly result from summer storms (Table 3-2). These few streamflow data available for the general study area were collected to document flooding. Locations of the gaging sites are shown in Figure 3-3, and data collected at these sites summarized in Table 3-2. (These sites and data are also discussed later in Section 3.2.) No data are presently available that relate runoff to recharge (see studies planned for Fortymile Wash area, Section 8.3.1.2.1.3), and the data are insufficient to develop meaningful flood recurrence intervals.

Quantitative data on rainfall, runoff, and evaporation for the area are not yet adequate to determine rainfall-runoff-recharge relations for individual storms, seasons, or years. Therefore, only general knowledge of runoff parameters is available. Numerical simulations of rainfall-runoff relations are possible, but these models cannot be calibrated until more field data become available. See Section 3.2.1.1 for a discussion of investigations

Table 3-2. Summary of peak streamflow data for selected crest-stage sites in hydrographic study area and adjacent areas[a] (page 1 of 2)

Site number[b]	Station number	Station name	Drainage area (mi^2)	Drainage area (km^2)	Period of record	Peak discharge (m^3/s)	Date of peak discharge	Discharge per unit area $((m^3/s)/km^2)$
1	10247860	Penoyer Valley tributary near Tempiute, Nevada	1.48	3.83	1964-80	3.68	8/06/68	0.96
2	10248490	Indian Springs Valley tributary near Indian Springs, Nevada	29.0	75.1	1964-80	14.1	8/14/72	0.19
3	10251270	Amargosa River tributary near Mercury, Nevada	110.0	284.9	1963-80	97.1	8/04/68	0.34
4	10251271	Amargosa River tributary No. 1 near Johnnie, Nevada	2.21	5.72	1967-80	9.9	8/04/70	1.73
5	10251272	Amargosa River tributary No. 2 near Johnnie, Nevada	2.49	6.45	1968-80	3.54	8/01/68	0.55
6	10251220	Amargosa River near Beatty, Nevada	470.0	1,217.0	1964-79	453.0	2/24/69	0.37

Table 3-2. Summary of peak streamflow data for selected crest-stage sites in hydrographic study area and adjacent areas[a] (page 2 of 2)

Site number[b]	Station number	Station name	Drainage area (mi^2)	Drainage area (km^2)	Period of record	Peak discharge (m^3/s)	Date of peak discharge	Discharge per unit area ($(m^3/s)/km^2$)
7	10249050	Sarcobatus Flat tributary near Springdale, Nevada	37.1	96.1	1961-80	1.78	9/09/80	0.02
8	10249850	Palmetto Wash tributary near Lida, Nevada	4.73	12.25	1967-80	5.46	7/07/69	0.45
9	10248970	Stonewall Flat tributary near Goldfield, Nevada	0.53	1.37	1964-79	4.25	6/16/69	3.10
10	10249680	Big Smoky Valley tributary near Blair Junction, Nevada	11.4	29.5	1961-79	4.81	10/02/76	0.16
11	10249135	San Antonio Wash tributary near Tonopah, Nevada	3.42	8.86	1965-80	18.7	8/13/72	2.10
12	10249180	Salsbury Wash Tonopah, Nevada	56.0	145.0	1962-80	9.62	3/27/69	0.07

[a] Source: Squires and Young (1984), and Waddell et al. (1984).
[b] Location of sites is shown in Figure 3-3.

CONSULTATION DRAFT

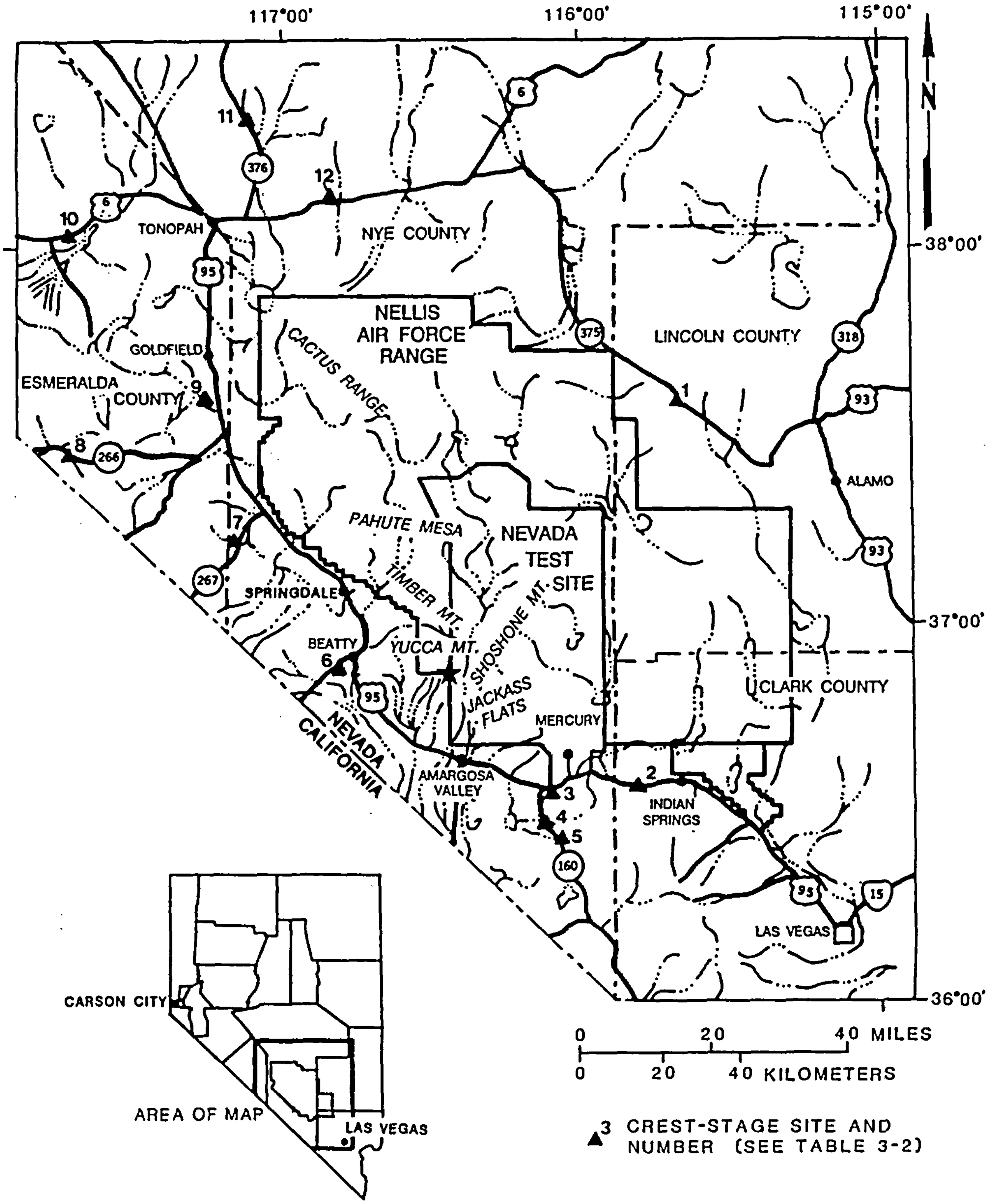


Figure 3-3. Locations of crest-stage sites in the hydrographic study area and adjacent areas. Modified from Squires and Young (1984).

currently underway to improve the surface-water hydrologic data base at Yucca Mountain and surrounding areas. Plans for future investigations and analysis of surface-water flow in terms of precipitation, runoff, infiltration, evaporation and transpiration, and floods are given in Section 8.3.1.2.1.

Throughout the hydrographic study area, perennial surface water comes only from springs, and it is restricted to some short reaches of the Amargosa River, to source pools at some large springs, and to some marshes around the edge of the salt pan in Death Valley (Hunt et al., 1966). One small lake, locally known as Crystal Reservoir, with a storage capacity of 2.27 x 10^6 m^3 (Giampaoli, 1986), occurs in the Ash Meadows part of the Upper Amargosa hydrographic area (Figure 3-1). The water for the reservoir is supplied via a concrete flume from Crystal Pool (Giampaoli, 1986).

The Amargosa River originates in Oasis Valley and continues southeastward through the Amargosa Desert past Death Valley Junction then southward another 75 km, where it turns northwestward and terminates in Death Valley (Figure 3-1). The river carries floodwaters following cloudbursts or intense storms but is normally dry, except for a few short reaches that contain water from springs (Walker and Eakin, 1963), in Oasis Valley between Springdale and Beatty (Malmberg and Eakin, 1962), in Ash Meadows northeast of Death Valley Junction, and near Shoshone, about 40 km south of Death Valley Junction. Springs are discussed in greater detail in Sections 3.3 and 3.5. Base flow to these segments of the river is maintained by ground-water discharge during the winter, when evapotranspiration is at a minimum. During the summer, discharge from the springs is almost entirely lost by evapotranspiration. During winter, ground water discharges into the river south of Alkali Flat near Eagle Mountain about 10 km south of Death Valley Junction (Walker and Eakin, 1963).

Because of the ephemeral character of streamflow, specifically in the Yucca Mountain area and generally throughout the Death Valley regional drainage systems, almost no streamflow data have been collected. The quantity of average annual runoff within the eight hydrographic areas in the Death Valley Basin in Nye County, Nevada, was estimated at less than 620,000 m^3 for each separate area (Scott et al., 1971). However, the magnitudes, frequencies, and durations of flows that comprise these average estimates are unknown. A discussion of the total water budget is given in Section 3.5. Plans for collection of streamflow data are discussed in Section 8.3.1.2.1.

Dry washes provide channels that concentrate runoff and may thus be the principal sources of potential modern ground-water recharge to the area. The implications and evidence of possible recharge by surface water are discussed in Section 3.9.3.3.

There are no manmade water-control structures that could influence conditions at the site, and none is known to be proposed.

3.2 FLOODS

Because of limited streamflow data in the hydrographic study area, the flood history of individual drainages tributary to Death Valley is not well known. Analysis of the general character of flooding is based on scattered data from peak-flow stations located around the Yucca Mountain area and from quantitative measurements of flood-flow peaks in a five-state region that comprises Arizona, California, Nevada, New Mexico, and Utah.

Flood analyses at Yucca Mountain are needed to provide flood data for design and performance considerations. Flood data will also be used to help evaluate infiltration rates and long term erosion rates. Two hydraulic engineering studies of flood-prone areas at and near Yucca Mountain (Christensen and Spahr, 1980; and Squires and Young, 1984) provided a basis for estimating the magnitudes of future floods with various recurrence intervals. The results of these investigations are presented in Section 3.2.1. Analytical methods other than those presented in ANSI/ANS 2.8-1981 (American Nuclear Standards Institute/American Nuclear Society) for estimating the potential for flooding of the site were used in these introductory studies; the reasons for applying alternate methods and a description of the procedures used are given in Section 3.2.1.

The measures that will be used to protect the site from floods are described in Section 3.2.2.

3.2.1 FLOOD HISTORY AND POTENTIAL FOR FUTURE FLOODING

Moderate to large floods in low-lying areas along the major drainages (drainage areas of several hundred square kilometers), such as the Amargosa River and Fortymile Wash, usually are the result of regional storm systems that most commonly occur during the winter and occasionally occur during autumn and spring. These extensive storm systems sometimes include areally restricted cells that discharge intense precipitation.

Flash floods of similar intensity and areal extent commonly occur as the result of summer thunderstorms. These summer floods usually do not cumulate to cause regional floods, but their intensive character renders them potentially destructive over limited areas. The summer storms are commonly the products of monsoonal air masses that invade southern Nevada and California from the general vicinity of the Gulf of California. The areally restricted storm cells are triggered by local convective lifting of the moist air or by cooler frontal systems that move through the region and intersect with the warmer monsoonal air mass. A detailed discussion on climatic conditions including precipitation, temperature, wind, and severe weather phenomena is given in Section 5.1.

In summary, although flooding can occur over an extensive area, intense floods are generally restricted to relatively small areas and occur as flash floods of short duration.

Flash floods constitute a hazard throughout the Great Basin (Chapter 1) and specifically in southern Nevada. These floods and associated debris flows are among the most important geomorphic processes currently active in the region and local area. They play a major role in the development of alluvial fans, denudation of mountainous landscapes, and the evolution of drainage-channel morphology. Flash-flood discharges range in character from water-dominated mixtures of sediments and water to debris flows. The hazards posed by debris movement associated with flash floods may be of equal or greater importance with regard to destructive potential than that of the mobilizing water. The intensive rainfall and runoff of flash flooding commonly promotes debris avalanching on steep slopes. Erosion scars caused by these debris avalanches are not uncommon in the Yucca Mountain area.

Data have been collected since the early 1960s on flooding and streamflow in ephemeral stream channels throughout Nevada. A network of crest-stage gages has been operated for almost two decades. Crest-stage gages are simple devices that record evidence of the peak-flow stage of a stream at the specific site where they are located. They do not record the duration of flow associated with the peak stage; also, they are poor indicators of multiple-peak stages that can occur between visits to the site. Also, because the network of gages was not dense, only a small percentage of ephemeral stream channels throughout Nevada has been monitored. Individual gages were visited monthly during this data collection program to ascertain recent occurrences of stream flow at the gage sites. If evidence of recent streamflow was noted during a visit, an indirect measurement of the peak-flow discharge was made and recorded along with the stage of the peak flow. Additional site visits were made when knowledge of recent flooding or major flooding was available. The resultant data base is a reasonably reliable record of the magnitude and frequencies of peak flows at the crest-stage gaging sites during the tenure of operation of the gages.

Twelve crest-stage gaging sites that were part of the monitoring network are located in the general area of Yucca Mountain. Locations of these sites are shown in Figure 3-3, and data collected at the sites are summarized in Table 3-2. Data collection at these sites was discontinued in 1980 when the statewide network was reduced. Stations 2 through 6 (Figure 3-3) have been reactivated as part of ongoing studies (Section 3.2.1.1).

Table 3-2 indicates that maximum unit peak-flood discharges (peak discharge divided by upstream drainage areas) measured at the 12 gaging stations during about a decade and a half ranged from approximately 0.07 $(m^3/s)/km^2$ for drainage areas greater than 100 km^2 to more than 3.0 $(m^3/s)/km^2$ for drainage areas less than 10 km^2. This evidence of recent flooding indicates that occasional locally intense runoff probably will occur in the future within southern Nevada, and may occur in washes at Yucca Mountain.

Several major floods that occurred in some of the washes from 1964 through 1980 are shown in Table 3-2. The most notable flood was associated with a large winter storm that occurred over the upper Amargosa River drainage basin (drainage area, 1,217 km^2) in February 1969. This storm caused an estimated peak flow of 453 m^3/s near Beatty with a peak discharge per unit area of 0.37 $(m^3/s)/km^2$ (estimated from records for site No. 6. The upper Amargosa drainage basin is immediately west of Fortymile Wash basin, and the two basins have similar physiographic terrains. A peak flow of 97.1 m^3/s with a peak discharge per unit area of 0.34 $(m^3/s)/km^2$ occurred in August 1968 at site No. 3 in an unnamed tributary to the Amargosa River near Mercury. This drainage basin has an area of 284.9 km^2; the basin terrain is also similar to that of Fortymile Wash.

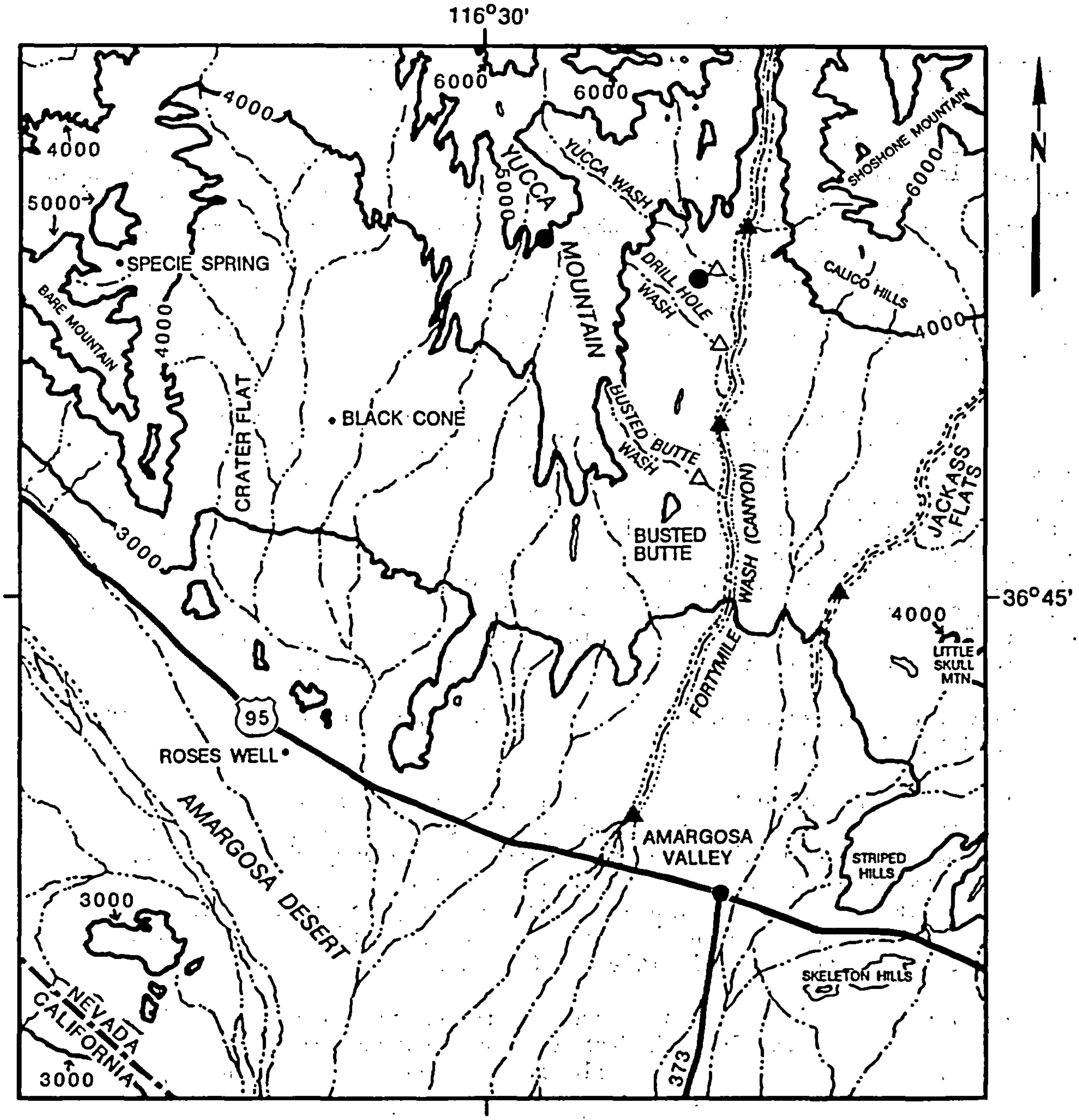
Long-range flood predictions are difficult to make, even for drainages that have stream-flow records as long as 100 yr. Predictions are especially difficult for drainages with minimal stream-flow records, such as those in the hydrographic study area. Current flood-prediction methods for this area generally involve some form of statistical evaluation of available regional stream flow, precipitation, modeling, and channel morphology data. These evaluations will be supplemented by studies of paleoflood sediments in order to provide a history of major paleofloods in the area (Section 8.3.1.5.2).

Analyses of the effects of probable maximum floods near the surface sites of proposed repository facilities have been initiated. An analysis was made of the flood plain of Fortymile Wash and its southwestern tributaries that include ephemeral stream channels from the east flank of Yucca Mountain (Figure 3-4) (Squires and Young, 1984). An analysis also was made of flood plains of Topopah Wash, a sizeable drainage from the Shoshone Mountain area into Jackass Flats, about 10 to 15 km east of Yucca Mountain (Christensen and Spahr, 1980). These studies of flooding potential of major desert washes are pertinent introductory investigations of flood potential at Yucca Mountain because of their close geographic and physiographic relations to that area.

Squires and Young (1984) estimate the magnitudes of the 100- and 500-yr flood peaks and the regional maximum peaks. The standard errors for the estimates of the 100- and 500-yr floods are relatively large. These relatively large errors result primarily from the short period of record (15 to 20 yr) and the extreme areal variability of floodflows in arid climates. However, the regression approach used by Squires and Young (1984), which is based on data from nearby streams, is believed to be the best available method for peak-discharge determinations. Other methods, such as rainfall-runoff modeling, may give results that are not qualified as to their statistical reliability. These other methods are not believed inherently better than the method used in the study of Squires and Young (1984), which allows a reliability evaluation and is based on nearby flood data. The estimated discharges for the 100- and 500-yr floods on Fortymile Wash and the three southwestern tributaries are considered accurate to no more than two significant figures (Squires and Young, 1984).

The estimates of regional maximum floods made by Squires and Young (1984) are based on a graphical boundary curve developed by Crippen and Bue (1977). The graph defines a boundary curve of maximum discharges that have occurred in drainages of varying sizes and is based on quantitative measurements of flood-flow peaks in a five-state region that includes Arizona, California, Nevada, New Mexico, and Utah. That graph is reproduced and modified by Squires and Young (1984) and includes data from southern Nevada.

The technique for calculating the probable maximum flood is based on a determination of maximum probable precipitation over the drainage or drainages being considered. It also requires detailed knowledge of the drainage basin to effect reasonable and accurate predictions of probable maximum peak flows. The sparse streamflow records, the availability of only minimal precipitation and storm data, and the absence of data on infiltration-runoff characteristics for drainage basins in the Yucca Mountain area requires that many speculations and assumptions would be needed to calculate the magnitudes of probable maximum floods in complex drainages the size of Fortymile Wash and Topopah Wash. Also, the lack of storm and runoff data throughout the



— TOPOGRAPHIC CONTOUR

▲ CONTINUOUS-RECORD GAGING STATION

△ PEAK-FLOW MEASUREMENT GAGING STATION

● CONTINUOUS-RECORD PRECIPITATION STATION

INTERMITTENT OR DRY STREAM

INCISED CHANNEL

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

NOTE: The following sites are beyond the boundaries of this map:

A continuous-record gaging station with continuous-record precipitation gage on an unnamed tributary to Fortymile Wash near Rattlesnake Ridge, about 46 airline km NNe of Busted Butte.

A peak-flow measurement gaging station on Cane Springs Wash, about 29 airline km ENE of Busted Butte.

Figure 3-4. Yucca Mountain area and current streamflow measurement sites Modified from Squires and Young (1984).

hydrographic study area prevents checking the validity of the various assumptions used.

Because of data limitations just discussed, the methods for predicting extreme discharges of unusually large floods as used by Christensen and Spahr (1980) and Squires and Young (1984) were considered preferable to the methods presented in ANSI/ANS 2.8-1981 at the time the flood studies were conducted for Topopah and Fortymile washes. A preliminary study has been done to evaluate the clear-water probable maximum flood discharge for the Yucca Mountain site (Bullard, 1986). Results of this study will be analyzed to evaluate the flood potential of the site. Further studies are planned and discussed in Section 8.3.1.16.1.

Squires and Young (1984) determined flood magnitudes and frequencies less than the regional maximum by statistically manipulating the measured data collected at the 12 sites of Table 3-2. The study by Christensen and Spahr (1980) defined flood-prone areas of 100-yr, 500-yr, and maximum potential floods for Topopah Wash and its tributaries in the eastern part of Jackass Flats (Figure 3-4). Their maximum potential flood is essentially equivalent to the regional maximum flood of Squires and Young (1984). Christensen and Spahr (1980) reproduced the curve developed by Crippen and Bue (1977) for the region including Yucca Mountain as their basis for determination of the magnitude of their maximum potential flood.

From their investigation of Topopah Wash, Christensen and Spahr (1980) concluded the following:

1. The areas prone to 100-yr floods closely parallel most main channels, with few occurrences of out-of-bank flooding of the areas between the main channel and adjacent secondary channels. Out-of-bank flooding would result in a water depth of less than 0.6 m, with a mean velocity as high as 2 m/s occurring on the steeper slopes. Flood-water depth in the stream channels would range from 0.3 to 2.7 m, with mean velocities of 0.9 to 2.7 m/s.

2. The 500-yr flood would exceed the discharge capacity of all stream channels except Topopah Wash and some upstream reaches of a few tributaries. Out-of-bank flooding of areas between the adjacent channels would result in water depths as much as 0.9 m, with mean velocities greater than 2 m/s. Flood-water depth in the stream channels would range from 0.3 to 3.7 m, with mean velocities ranging from 0.9 to 4 m/s.

3. The maximum potential flood would inundate most of Jackass Flats. Out-of-bank flows in the areas between adjacent channels would have a depth as much as 1.5 m, with a mean velocity as high as 4 m/s. Flood water in the stream channels would have depths of 0.6 to 7 m, with velocities of 1.2 to 7.9 m/s.

Squires and Young (1984) studied the downstream part of Fortymile Wash. Within this area, Fortymile Wash has three tributaries that are informally designated from south to north as Busted Butte Wash, Drill Hole Wash, and Yucca Wash. Approximate flood-prone areas in these washes are shown on Figure 3-5. Squires and Young (1984) conclude the following:

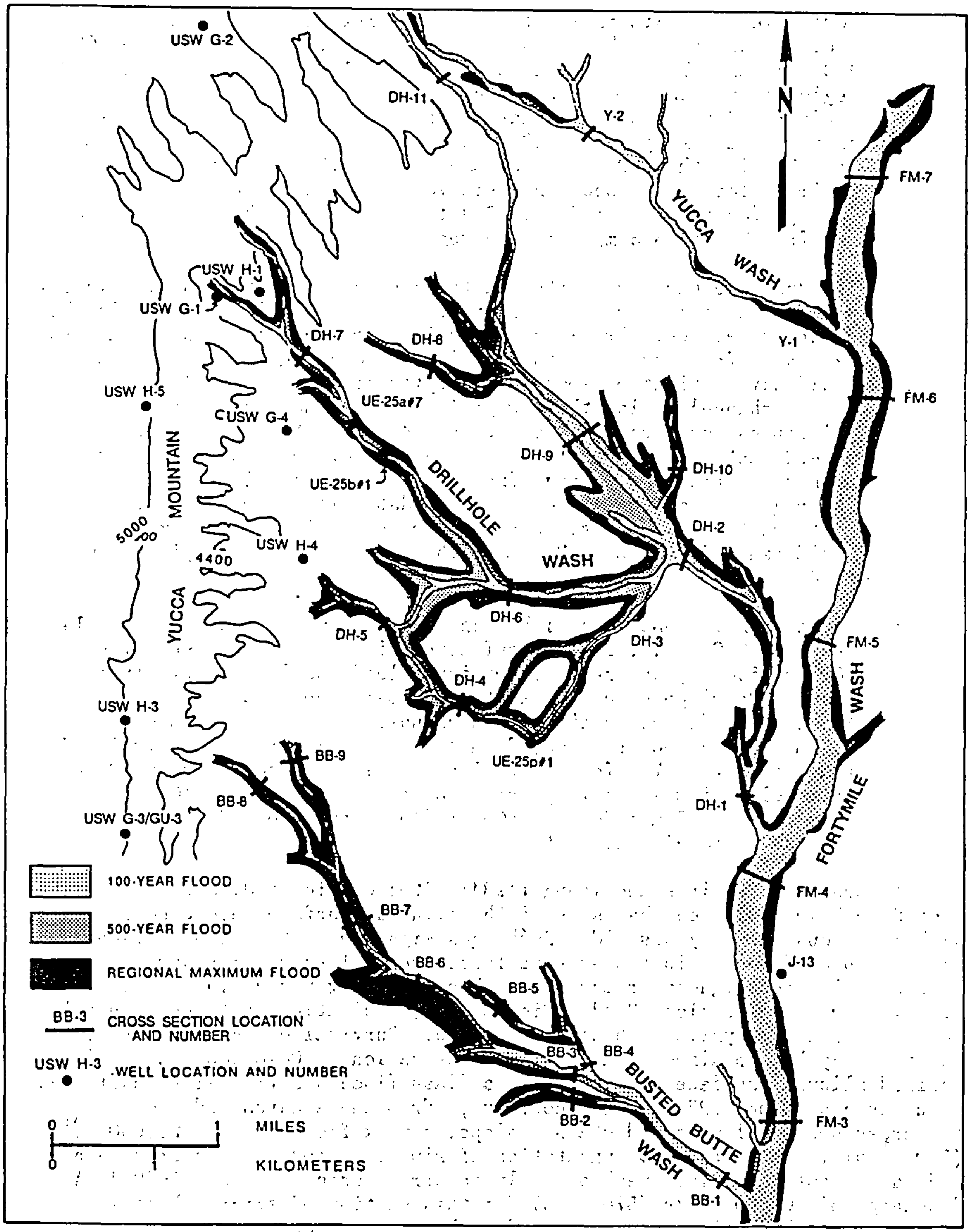


Figure 3-5. Flood-prone areas in the vicinity of Fortymile Wash. Modified from Squires and Young (1984).

1. Fortymile Wash, within the flood-study area, is a well-defined incised channel, with a cross section of 15 to 21 m depth and 300 to 450 m width. The estimated values of the 100-yr, 500-yr, and regional maximum floods indicate that the flow would stay within the confines of the wash. Estimated depths of flood water in the stream channel would range from 0.9 to 2.4 m for the 100-yr flood, from 1.8 to 3.3 m for the 500-yr flood, and 6.4 to 8.8 m for the regional maximum flood; corresponding mean velocities would be from 1.8 to 2.7 m/s for the 100-yr flood, 3.3 to 4.3 m/s for the 500-yr flood, and from 7.0 to 8.5 m/s for the regional maximum flood.

2. The drainage basin of Busted Butte Wash varies from a shallow valley with meandering ephemeral streams to a deeply incised canyon in the upstream reaches. Drill Hole Wash is characterized by deep canyons extending from Yucca Mountain to its mid-drainage area. Both washes would have estimated flood-water depths of from 0.3 to 1.2 m in the stream channel during the 100-yr flood, and the corresponding mean velocities would range from 1.2 to 2.4 m/s. The 500-yr flood would exceed bank capacities at several reaches of the washes. Depths and mean velocities would range from 0.9 to 3.0 m and 1.5 to 3.3 m/s. The regional maximum flood would inundate all central flat-fan areas in these two watersheds. Flood-water depths in the stream channels would range from 1.5 to 3.7 m, with mean velocities varying from 2.1 to 4.9 m/s.

3. Yucca Wash is contained within an incised channel that is about 14 m deep and 240 m wide at its confluence with Fortymile Wash. The 100-yr, 500-yr, and regional maximum floods would stay within the steep-side-slope stream banks that contain the flood plain. Flood-water depths in the stream channel would range from 0.9 to 1.5 m for the 100-yr flood, from 1.5 to 2.7 m for the 500-yr flood, and from 2.7 to 7 m for the regional maximum flood; corresponding mean velocities would vary from 1.5 to 2.7 m/s for the 100-yr flood, from 2.4 to 3.7 m/s for the 500-yr flood, and from 2.7 to 6.7 m/s for the regional maximum flood.

According to Squires and Young (1984), "Geomorphic studies on the Nevada Test Site have indicated that some of the alluvial surfaces along Fortymile Wash are thousands of years old. Such ages might imply that the surfaces have not been flooded since they were formed several thousand years ago. However, distinct high-water marks are observed along Fortymile Wash in the vicinity of cross-section FM-4" (Figure 3-5), indicating that the alluvial surfaces along Fortymile Wash were inundated. Survival of these alluvial surfaces may be explained by a previous observation in Colorado that a fine-grained alluvial surface overtopped by a flash flood was virtually unaffected (Squires and Young, 1984). They continue, "From these marks and from data on the cross-sectional area and channel slope, a peak flow of about 20,000 ft^3/s (570 m^3/s) is estimated. Documentation of similar flooding in nearby washes indicates that this flood peak probably occurred during February 1969." A discharge of 20,000 ft^3/s (570 m^3/s) for this section of stream channel is greater than the estimated discharge for the 100-yr flood (12,000 ft^3/s (340 m^3/s)), but less than the estimated discharge for the 500-yr flood (57,000 ft^3/s (1,600 m^3/s)) (Squires and Young, 1984). Additional studies are planned to evaluate paleoflooding in the Yucca Mountain area through the use of geomorphic and geologic evidence. These studies are discussed in Section 8.3.1.5.2.

The extent of erosion and sediment movement caused by flood flow in Fortymile Wash and its tributaries that drain Yucca Mountain is not known quantitatively. Qualitatively, however, on the basis of knowledge of record major floods elsewhere in southern Nevada (Glancy and Harmsen, 1975; Katzer et al., 1976), erosion of or deposition in channels and flood plains probably would occur during the 100-yr, 500-yr, and regional maximum floods. While erosion or deposition due to an individual flood event cannot be quantified, average rates of stream incision over long periods of time can be evaluated. Section 1.1.3.3.2 discusses surficial processes, and Table 1-3 lists average rates of stream incision in the Yucca Mountain area.

Evidence of erosion and deposition was observed in some channels during field surveys. Channel erosion or aggradation in the existing streambeds could alter the flood-flow characteristics of cross-sectional area, width, mean velocity and maximum depth listed in the report by Squires and Young (1984). The effect of erosion or deposition on flood-flow characteristics would vary from place to place. Because velocities for the 100-yr, 500-yr, and regional maximum flood peaks are high, channel erosion and aggradation appear likely.

Because most of Yucca Mountain is well above expected flood levels of Fortymile Wash and its major tributaries, as assessed by Squires and Young (1984), numerous small ephemeral stream channels from the mountain to the major drainages were not included in their study. Flow in the ephemeral stream channels that may affect the Yucca Mountain site will be assessed in future studies (Section 8.3.1.2.1).

The sparseness of the historic data base on surface-water hydrology, including the movement of both water and debris inhibits accurate prediction of flood and debris hazards for the immediate future. Data needs, plans for future data collection, and data-collection methodologies are given in Section 8.3.1.16.1. Likewise, a deficient understanding of paleoclimates (Section 5.2.1) and past geomorphic processes (Section 1.1.3) limits the ability to predict climatic changes and their probable effects on flood-and-debris-hazards potential over the next several thousands of years. Plans for studies of future climates are discussed in Section 8.3.1.5.1.

Hydrologic conditions that have occurred during the Quaternary that have differed from present conditions, and the likelihood of recurrence over the next 10,000 yr, are described in Sections 3.7.4 and 3.9.8. Evidence for long term changes in hydrometeorology are discussed in Section 3.7.4. A more detailed discussion on past influences of glacial environments in the western United States and their effects on climate is given in Section 5.2. Hoover et al. (1981) describes a system for correlating and mapping surficial deposits in the Yucca Mountain area. The stratigraphic sequence of units, soils, and unconformities that has been observed indicates fluctuating climatic conditions.

3.2.1.1 Ongoing and future studies of flood and debris hazard potentials

Studies are planned to improve the surface-water hydrologic data base at Yucca Mountain and surrounding areas (Section 8.3.1.2.1). The minimal data on stream flow and insufficient knowledge of geomorphic parameters make predictions of flood and debris hazards very speculative. To rectify this deficiency, the NNWSI Project plans to expand the streamflow (movement of water and debris) data base (Section 8.3.1.2.1). A network of stream-gaging stations near Yucca Mountain has been established to monitor and record modern stream flows. Four continuously recording stream gages and five peak-flow gages were installed. Locations of these gages are shown in Figure 3-4. Precipitation gages also installed at these stream gaging sites collect rainfall data. Also, five peak-flow gages at sites 2 through 6 (Table 3-2 and Figure 3-3) have been reactivated. Investigations of flooding also provide stream flow data at other miscellaneous ungaged sites when floods occur near Yucca Mountain or the surrounding region. These investigations also yield data on debris transport, particularly where debris avalanches or debris flows are part of the flooding process.

Investigations of paleofloods, including debris flows, have been initiated. Paleoflood studies involve analyses of sediment deposits of Quaternary floods and collection of evidence for mass movement of debris by these floods. These investigations are being conducted to improve understanding of Quaternary runoff events, develop a chronology of flooding, provide data on past geomorphic processes for comparison with modern processes, and aid in interpretation of paleoclimates. Plans for future investigations of, and data collection for potential flood and debris hazards, are described in Section 8.3.1.5.2.

Inasmuch as the Yucca Mountain area is located inland and has no significant surface-water bodies or water-control structures located near the site, there is no potential for events such as surges, seiches, tsunamis, dam failures, or ice jams that could affect the site, nor is there any potential for future dam development. The Yucca Mountain area was not glaciated during the Pleistocene (Section 5.2). No evidence for pluvial lakes has been found in the Yucca Mountain area (Mifflin and Wheat, 1979). This indicates that the potential for floods during maximum glaciation is minimal. Additional studies to evaluate the potential for climatic change and the effects of any change on the proposed site are discussed in Section 8.3.1.5.2. No evidence for past flooding induced by landslides in the vicinity of the site has been reported (USGS, 1984, and Section 1.1.3, geomorphic processes).

3.2.2 FLOOD PROTECTION

The rugged terrain at the Yucca Mountain site and local convective storms can cause intense flooding to occur periodically in the normally dry washes that drain Yucca Mountain ridge. Protection from this flooding was considered in choosing the proposed locations for the surface facilities, shafts, and ramps in the current conceptual design. Topographic maps with 20-ft contour intervals on a 1:24,000 scale were used, together with direct observations, to choose the proposed locations. These maps, however, do not provide the detail necessary for final design. New topographic maps have been compiled (Wu, 1985) of the Yucca Mountain area at a scale of 1:5,000 and a contour interval of 2 m (with 1-m supplemental contours). These will be used for some aspects of final design.

As described in Section 6.2.4.2 (flood protection) a preliminary analysis of the probable maximum flood (PMF), based on a study by Bullard (1986), has been performed for the men-and-materials shaft area because of the local rugged terrain and the proximity of the shaft area to the confluence of two washes that are tributary to the larger Drill Hole Wash. The purpose of the preliminary analysis was to evaluate the feasibility of locating the shaft and its supporting surface complex in such a rugged area. In the analysis, the PMF flows and levels were conservatively estimated and flooding protection provisions were incorporated into the design. The men-and-materials shaft area is benched, with the shaft entrance designed to be above the PMF levels in the diversion channels, located on the north and south sides, as well as the PMF level in Drill Hole Wash. From this preliminary conservative analysis it was concluded that the men-and-materials shaft can be adequately protected from PMF levels at the proposed location.

Further surface facility design will be based on PMF flows and levels, determined in accordance with ANSI/ANS 2.8-1981. This site information will be acquired in accordance with site characterization plans described in Section 8.3.1.14.1, topographic characteristics of potential locations of surface facilities, and Section 8.3.1.16.1, flood-recurrence intervals and levels at potential locations of surface facilities. This design effort will be finalized when definitive flooding data become available, as described in Section 8.3.2.5.7, design analyses including those addressing impacts of surface conditions, rock characteristics, hydrology, and tectonic activity.

3.3 LOCATIONS AND DISTANCES TO POINTS OF SURFACE-WATER USE

The purposes of Section 3.3 are to (1) identify the locations and quantities of the surface water currently used for supply, and (2) project the amounts of surface water that will be used during the next 50- and 100-yr periods. The general absence of surface water that is suitable for supply purposes, precludes addressing those aspects of surface water that are directly related to water supply for populations (i.e., extracted quantity of water, extraction locations, size of population served, projected populations and corresponding water-use figures, etc.).

The hydrographic study area (Figure 3-1) includes all occurrences of surface water that may be affected by or affect site characterization and repository construction and operations. This section presents all known sources of surface water within the hydrographic study area, the quantity and quality of available surface water, and current and projected water needs of industrial, commercial, municipal, agricultural, and domestic water users.

3.3.1 PRESENT QUANTITY AND QUALITY OF SURFACE WATER EXTRACTED

Very little surface water exists in the vicinity of Yucca Mountain. The climate in the region is arid; no perennial streams are present except short reaches of the Amargosa River which are fed by springs (Figure 3-1) (Waddell et al., 1984). Other perennial sources of surface water are the small spring-fed ponds in Oasis Valley, the Amargosa Desert, and Death Valley (French et al., 1984; Waddell et al., 1984). Spring locations and their water chemistries are presented in Sections 3.5.1 and 3.7.3, respectively. Spring water use is discussed in Section 3.8.1.

Several small, man-made reservoirs used for agricultural, milling, and mining purposes are scattered throughout the southern portion of the hydrologic study area. The largest, a man-made reservoir, known locally as Crystal Reservoir, is located in the Ash Meadows area 52 km (32 mi) southeast of Yucca Mountain (Figure 3-1). This reservoir receives its water from Crystal Pool spring, located approximately 0.8 km (0.5 mi) to the north. Crystal Reservoir, which has a capacity of 1,840 acre-feet (2.27×10^6 m^3) is used for recreational purposes only. Another small reservoir (Clay Camp at NE 1/4, Section 1, T.18S., R.49E.) with a capacity of 43 acre-feet (53,000 m^3), is used for milling. This and many other reservoirs are fed by wells (Section 3.8.1). Other small reservoirs with capacities much less than 40 acre-feet (49,300 m^3) exist near Point of Rocks and Death Valley Junction (Giampaoli, 1986).

The Amargosa River (Section 3.1) is not used for water supply. The flow regime has been intermittent to ephemeral throughout historic times, except for the spring-fed reaches. As such, sufficient supplies for domestic, municipal, commercial, agricultural, or industrial supply have not been available (Walker and Eakin, 1963). The chemical composition of Amargosa River water is discussed in Section 3.4.

Hydroelectric power is generated at Hoover Dam near Boulder City, Nevada. Although Hoover Dam is located only 180 km southeast of Yucca Mountain, the hydrologic settings of the two areas are very different. The absence of a perennial river within the boundaries of the hydrographic study area precludes the development of hydroelectric power.

No other sources of surface water exist within the hydrographic study area. Frenchman Lake and Yucca Lake are playas that contain water only after rainstorms. Runoff to these playas serves to recharge the valley-fill aquifer (Claassen, 1985; Section 3.7.1). However, because of the sporadic precipitation and runoff and the excessive amounts of dissolved solids, playas are not considered as possible sources of water supply (Waddell et al., 1984). The virtual absence of perennial surface water has precluded its application for beneficial use in the hydrographic study area.

3.3.2 PROJECTED SURFACE-WATER USES

Arid conditions of the region and the absence of perennial streams and lakes make surface water an unlikely future water supply. Within the hydrographic study area, surface water serves two principal functions:

(1) recharge to the valley-fill aquifer and (2) maintenance of habitats for aquatic species. Surface-water use by man in the study area would probably increase only in the event of a change in climate to a wetter regime. Studies done to date indicate that such an event is possible, but not in the period of repository construction, operation, closure, and decommissioning (DOE, 1986) (see Section 5.2 for a complete discussion of climatic modeling and Section 8.3.1.5.1 for a discussion of planned studies). Consequently, there are no known plans to construct dams or reservoirs in the vicinity of Yucca Mountain site.

3.4 CHEMICAL COMPOSITION OF ADJACENT WATERCOURSES

This section addresses the chemical composition of surface water at the Yucca Mountain site and vicinity. Classically, the section would include discussions of (1) seasonal cycles of physical and chemical limnological parameters, (2) bottom and shoreline configuration, (3) sedimentation rates, (4) sedimentation graduation analysis, and (5) sorption properties. However, because of the arid to semiarid climate of the region, these topics are not applicable. This section presents data required to address questions of the adequacy of the description of the present and expected hydrogeologic characteristics in order to provide the information required by the design and performance issues and the formation of a sufficient baseline against which to assess potential impacts.

The historical records and onsite monitoring of surface water composition is quite limited. Present data consist of two historic and six recent chemical analyses. The analyses are presented here along with discussions on trends and observations.

Within the hydrographic study area, the Amargosa River is the major surface-water source to the regional drainage sink of Death Valley. As described in Section 3.1, the Amargosa River is normally dry, except for short reaches that receive water discharging from the underlying ground-water flow system. Because of the ephemeral character of the Amargosa River only two water samples have been collected; one from a reach near Eagle Mountain and the other from Carson Slough, a major tributary that joins the Amargosa River near Alkali Flat (Figure 3-6). From the chemical analyses presented in Table 3-3, it can be seen that sodium and bicarbonate are the primary constituents. The high sulfate and chloride is indicative of ground-water interaction with playa deposits. The chemical composition of these two surface water samples is quite similar to that of the water from the tuffaceous valley fill aquifer (Section 3.7.3). This similarity suggests that the source of the water sampled is the tuffaceous valley fill. Hunt et al. (1966) indicate that ponding occurs where the shallow ground-water table in southern Amargosa Desert encounters a structural barrier north of Eagle Mountain.

Samples of surface water from the Yucca Mountain area were collected during period of runoff and flooding in July and August of 1984. Water samples were collected from the main stream channel of Fortymile Wash and from two of its principal tributaries, Drill Hole and Busted Butte washes (Figure 3-6). Results of analyses are shown in Table 3-3. All the samples

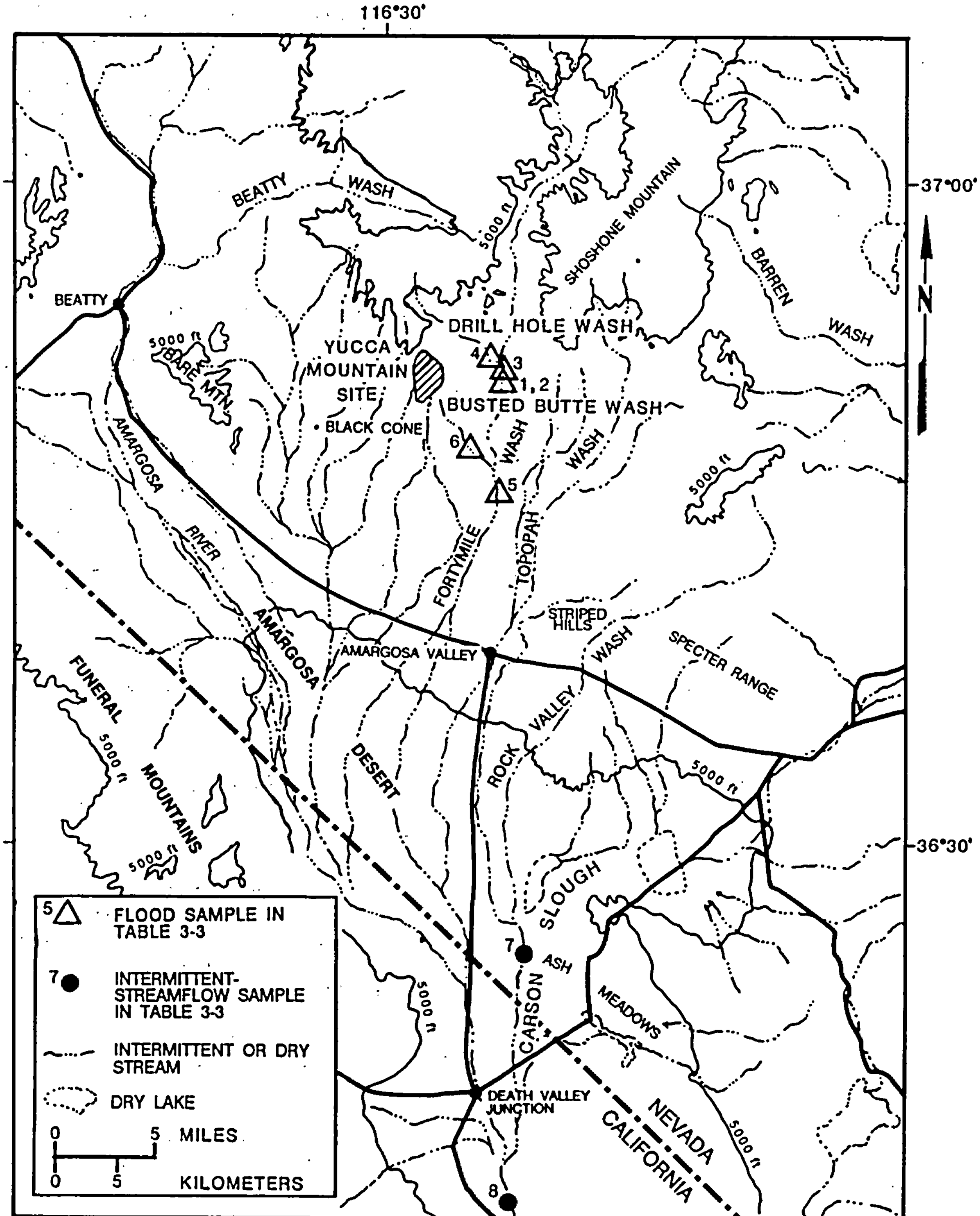


Figure 3-6. Surface-water sample sites listed in Table 3.3.

Table 3-3. Chemical composition of watercourses adjacent to Yucca Mountain[a]

Parameter	1 Flood sample Fortymile Wash at road M[b]	2 Flood sample Fortymile Wash at road W[b]	3 Flood sample Fortymile Wash above Drill Hole Wash[b]	4 Flood sample Drill Hole Wash at mouth[b]	5 Flood sample Fortymile Wash at J-12[b]	6 Flood sample Busted Butte Wash[b]	7 Stream sample Carson slough[c]	8 Stream sample Amargosa River near Eagle Mountain[c]
Laboratory sample number	4212602	4248608	4248604	4248605	4248607	428606	3060	3062
Latitude	36°49'07"	36°49'04"	36°49'08"	36°49'11"	36°49'51"	36°47'49"	≈36°25'	≈36°13'
Longitude	116°23'47"	116°23'47"	116°23'46"	116°23'52"	116°23'51"	116°23'51"	≈116°21'	116°22'50"
Site number on Figure 3-6	1	2	3	4	5	6	7	8
Date	7/22/84	8/15/84	8/14/84	8/14/84	8/14/84	8/14/84	1958	1958?
Specific conductance, field (microsiemens per cm at 25°C)	--[d]	170	70	100	59	120	937	1,860
Specific conductance, laboratory (microsiemens per cm at 25°C)	201	859	198	218	100	217	--	--
pH, field	--	8	8.4	8.3	8.2	8.3	8.5	8.8
pH, laboratory	7.4	7.4	7.5	7.8	7	7.8	--	--
Temperature (°C)	--	21.5	--	--	--	--	10	4.4
Calcium (Ca)	24	31	8.1	9.5	6.7	12	40	24
Magnesium (Mg)	3.3	2.9	0.9	1.3	0.7	1.8	26	29
Sodium (Na)	8.1	8.2	4.1	8.6	2.4	7	125	344
Potassium (K)	7.8	9.1	5.6	7.4	6.3	8.1	16	40
Bicarbonate (HCO_3)	--	--	--	--	--	--	362	542
Carbonate (CO_3)	--	--	--	--	--	--	10	33
Alkalinity as $CaCO_3$, lab	73	75	36	42	26	47	--	--
Chloride (Cl)	3.7	1.4	1.3	2.2	2	1.7	40	123
Sulfate (SO_4)	10	10	6.2	13	6.3	7.9	122	277
Fluoride (F)	0.2	0.2	<.1	0.3	<.1	0.3	2	2.8
Silica (SiO_2)	25	24	8.7	20	4.5	23	28	26
Arsenic (μg/L as As)	2	2	<1	2	<1	3	0.0	20
Iron (μg/L as Fe)	110	77	18	100	28	200	210	450
Manganese (μg/L as Mn)	3.3	5	11	6	22	10	0.0	0.0
Strontium (μg/L as Sr)	100	100	34	66	31	86	1,800	800
Lithium (μg/L as Li)	6	7	6	14	5	17	--	--
Iodide (I)	0.009	0.005	0.003	0.002	0.004	0.003	--	--
Bromide (Br)	0.049	<0.01	<0.01	<0.01	<0.01	<0.01	--	--
Boron (B)	--	--	--	--	--	--	0.68	2.1
Dissolved solids (sum)	127	122	57	92	45	100	566	1,140

[a]Values for chemical constituents are in milligrams per liter unless otherwise indicated. Analyses by U.S. Geological Survey, Denver, Colorado.

[b]Flood sample analyses (USGS) from WATSTORE files.

[c]Stream sample analyses from Hunt et al. (1966).

[d]-- indicates no data.

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are dilute and are significantly lower in solutes than ground-water samples of the area (Section 3.7.3). However, samples 1 and 2 are noticeably more concentrated in calcium and dissolved solids than are samples 3 through 6. This difference is most likely attributed to the fact that samples 1 and 2 were collected on different days than samples 3 through 6, which means that they are not only from different locations but also from different rainfall events. Even with the last four samples showing remarkably similar compositions, any quantitative interpretation is unwarranted unless the following are known:

1. The compositional variability of storms throughout the year.

2. The compositional variability within a given storm.

3. The lithologic composition of the source areas for the drainage systems.

However, the data do provide information about the base level composition of recharge to the valley-fill aquifer along Fortymile Wash (Section 3.7.3).

Waddell et al. (1984) cite water chemistry data that indicate that washes may be the principal source of ground-water recharge beneath Yucca Mountain. Periodic temperature measurements made in wells in Drill Hole Wash during 1981 to 1983 revealed a pronounced increase in the temperature profile above a depth of 150 m in drillhole UE-25a#7. This occurrence of warmer water may be related to recharge from a major storm that occurred early in March, 1983 (Waddell et al., 1984). Furthermore, as discussed in Section 3.7.3.2, the high tritium concentration of water from well UE-29a#1 in Fortymile Wash (62 tritium units) indicates that precipitation containing bomb-test tritium has recharged the aquifer since the mid-1960 possibly correlating with the major flood in the winter of 1969 (Section 3.2.1). This evidence clearly establishes that modern rainfall and runoff contribute recharge to the shallow ground-water system in the tuffaceous valley-fill aquifer. The extent of this contribution, which probably is small, cannot be further quantified with the existing data. Stable isotopic composition of surface water may also be used to interpret times and conditions of recharge. Planned studies for characterization of the regional surface water are discussed in Section 8.3.1.2.1.

3.5 POINTS OF GROUND-WATER DISCHARGE

Ground-water discharge from basins within the hydrogeologic study area occurs as spring flow, evapotranspiration, ground-water withdrawal, and outflow to other ground-water basins. This section discusses these various forms of discharge in relation to the overall hydrologic budget and identifies naturally occurring springs, seeps, and areas of phreatophytic growth that are located within the hydrogeologic study area. An inventory of water-supply wells located within the study area is presented in Section 3.8.1, as are discussions of spring and well water use. The discharge rates of specific springs are available in the spring inventory, presented later in this section. Ground-water underflow figures and the associated data from which they were calculated are included in Section 3.7. Ground-water withdrawals from specific wells are listed in Section 3.8.1. A discussion of the potential for contamination of ground-water and surface-water supplies that might result from site characterization activities is also included.

Throughout this section, the term ground water refers to one of several classifications of water lying beneath the surface, including deep and shallow saturated zones, unsaturated zones, soil water and perched water. The particular usage depends on the topic of discussion and may be derived from the context.

The data presented in this section generally address the question of the isolation of radioactive waste from the accessible environment after closure of the mined geologic disposal system at Yucca Mountain (Key Issue 1). More specifically, data concerning the location and nature of points of ground-water discharge may be used to assist in the identification of paths of likely radionuclide travel and in the calculation of ground-water travel time along those paths. Further, this information contributes to the description and understanding of the hydrologic system (both the unsaturated and saturated zones) and to the prediction of potential impacts to the quality and availability of water resources in the vicinity of Yucca Mountain.

In general, definitive discharge data for the hydrogeologic study area are scanty. Walker and Eakin (1963) estimated discharge in the Amargosa Desert; Malmberg and Eakin (1962) made similar estimates for Oasis Valley. These estimates are summarized in Table 3-4. But, because in this instance, it is not possible to separate all the various forms of discharge, the figures presented are intended for comparison purposes only and may not represent the actual conditions present in the two areas.

Evapotranspiration in the Amargosa Desert is approximately 1.4 times greater than spring discharge and 47 times greater than ground-water underflow. In Oasis Valley, evapotranspiration exceeds spring discharge and underflow by factors of 10 and 5, respectively. It is evident from these estimates that evapotranspiration is the primary mechanism for discharge of ground water in these areas and probably throughout the hydrogeologic study area. Surface discharge is not considered significant, because it is ephemeral (Malmberg and Eakin, 1962; Walker and Eakin, 1963). A further discussion is given in Section 3.1. However, the existing data are insufficient to quantify properly the surface-water component of the total discharge. To address this deficiency, site characterization activities will include measurements of overall runoff and the estimation of peak runoff, flood magnitudes, and recurrence intervals. The scope of work and timetable for these activities are discussed in Section 8.3.1.2.1. These plans allow for the ephemeral nature of desert runoff, including the possibility of no runoff events in any single year.

Table 3-4. Ground-water discharge from the Amargosa Desert and Oasis Valley

Discharge category	Amargosa Desert[a]		Oasis Valley[b]	
	acre-ft/yr	m^3/s	acre-ft/yr	m^3/s
Average annual consumptive use by native vegetation	11,500	0.45[c]	ND[d]	ND
Evaporation from soil	12,000	0.47	ND	ND
Total evapotranspiration	23,500	0.92	2,000	0.08
Surface-water runoff discharging from basin	ND	ND	ND	ND
Spring discharge	17,000[c]	0.66	200[e]	0.008
Ground-water underflow	500	0.02	200	0.016

[a]Source: Walker and Eakin (1963).
[b]Source: Malmberg and Eakin (1962).
[c]Total spring discharge, includes water becoming underflow, evapotranspiration, etc.
[d]ND = no data.
[e]Discharge from one spring that lies near the discharge point of the basin.

Several authors have used a variety of techniques to determine the average annual recharge rate for the area encompassing Yucca Mountain. Montazer and Wilson (1984) estimate the average annual recharge rate for Yucca Mountain to be between 0.5 and 4.5 mm/yr on the basis of various published estimates for the region. Using the analyses of Rush (1970), Czarnecki (1985) estimated recharge to be 0.7 mm/yr in a precipitation zone that includes Yucca Mountain. Czarnecki (1985) used a value of 0.5 mm/yr for modeling baseline conditions. Wilson (1985) concludes that 0.5 mm/yr is a reasonable and conservatively large value for flux below the proposed repository horizon at Yucca Mountain. This estimate is based on regional estimates, ground-water model studies, site data, and comparisons with published estimates for other arid and semiarid sites throughout the world. Nichols (1986) determined that recharge near Beatty may have occurred as three discrete pulses during the period 1961 to 1976. By implication, Nichols (1986) acknowledges the high probability that infiltration may not occur a majority of the time. Nichols (1986) estimated pulses of 2.2, 0.5, and 2.6 cm by comparing available precipitation, evaporation, and soil-moisture content data. The discrete pulses were expected to be dampened out with depth. Rice (1984) used a hydrologic budget technique to estimate recharge for a hydrologic model of the NTS and vicinity. Her calculations estimated recharge to the saturated zone at less than 2.5 mm annually. However, Rice's (1984) model lacked sufficient detail to be used as an accurate representation of the conditions present at Yucca Mountain.

An evaluation of all water inputs and outputs in the hydrogeologic study area aids in the estimation of infiltration to the unsaturated zone at the Yucca Mountain site. A regional hydrologic budget is one method of estimating the amount of water that enters, percolates through, and recharges the saturated zone beneath Yucca Mountain. Recharge volumes represent only a small percentage of the total precipitation. Thus, when estimates of recharge are based on precipitation data, high accuracy of the data is required to keep the recharge estimates from being masked by the uncertainty in the precipitation data. Collecting highly accurate precipitation data is difficult. Also, maintaining a high level of accuracy for other elements of the water budget (e.g., ground-water underflow or total evapotranspiration) probably is unrealistic. This method will be used to the extent possible using both available data and that obtained during site characterization. Determination of recharge to the saturated zone may be accomplished by a variety of other methods, some of which are discussed in Sections 3.7 and 3.9.

The hydrologic budget for recharge within the study area, under steady state conditions, may be defined as follows (based on Fetter, 1980):

$$R_G = Ppt + I - Et - Q_G - Q_S - Q_W \pm \Delta S_S \qquad (3\text{-}1)$$

where

R_G = ground-water recharge

Ppt = precipitation

I = surface- and ground-water inflow

Et = total evapotranspiration

Q_G = ground-water outflow

Q_S = surface-water runoff

Q_W = ground-water withdrawal

ΔS_S = changes in surface-water storage.

Under equilibrium conditions ground-water withdrawal is not considered and changes in the surface-water storage are considered to be zero.

As indicated, precipitation and inflow (surface and ground water) are the input factors to the total budget. Precipitation records, along with other climatological data, are available for the study area and are discussed in Section 5.1. Surface inflow from outside the boundaries of the hydrographic study area does not occur (Section 3.1). Ground-water inflow, however, has not been adequately quantified for the study area and will be studied during site characterization. Estimation of this component of the hydrologic budget will be accomplished through hydrologic modeling as discussed in Section 8.3.1.2.1.

Although discharge through surface-water runoff and ground-water outflow are smaller components of the total discharge, they are equally important for proper quantification of the total discharge. However, the data for the study area are not sufficient to quantify inflow, outflow, and runoff, or to relate these to recharge. Net subsurface flux (outflow minus inflow) must be quantified for proper comparison of recharge versus outflow from the basin. Plans for these studies are discussed in Section 8.3.1.2.1. Surface runoff and ground-water outflow are discussed further in Section 3.1, 3.2, and 3.7.

Total evapotranspiration is the sum of several processes (Robinson, 1957).

$$Et = E_s + E_i + E_x + E_p + E_c + E_{sw} \qquad (3\text{-}2)$$

where

Et = total evapotranspiration

E_s = evaporation from soil

E_i = evaporation of precipitation intercepted by foliage

E_x = transpiration by xerophytes

E_p = transpiration by phreatophytes

E_c = evaporation from capillary fringe

E_{sw} = evaporation from surface water.

Although evaporation from soil has not been sufficiently quantified in the study area, available studies indicate that losses due to evaporation from soil may be an important factor in the water budget. In a study by Nichols (1986), soil evaporation near Beatty was estimated to average 97 percent of the annual precipitation during the period 1961 to 1976. Further, Nichols (1986) stated that the high evaporation rate may have allowed for only three recharge events during the 16-yr study period.

The discharge of ground water through bare-soil evaporation can be significant, especially in areas with a shallow water table. Such conditions do not exist in the immediate vicinity of Yucca Mountain. However, shallow ground water does occur within the hydrogeologic study area. Ripple et al. (1972) present a method for estimating evaporation from bare soil areas with a near-surface water table. The procedure is potentially useful for estimating evaporation from areas such as Alkali Flat. An important factor in assessing evaporation from soil is the availability of detailed soil-type and surficial-deposits maps. These are, for the most part, unavailable for the study area. However, Swadley et al. (1984) describe the surficial deposits near Yucca Mountain. Additional assessment of soil-moisture losses and mapping of surficial deposits will be included in site characterization activities as discussed in Section 8.3.1.5.1.

Data concerning evaporation of intercepted precipitation are not available for the study area. Investigations of this process in Utah and Idaho (Hull and Klomp, 1974; West and Gifford, 1976) report average water-holding capacities for individual sagebrush plants of 1.5 mm. Within the study area, the limited plant density (average shrub coverage ranging from 16 to 29 percent depending on elevation (O'Farrell and Emery, 1976)) and small crown diameters indicate that this element of the water budget is relatively minor, but not insignificant, particularly compared with the average annual recharge estimate of 0.5 mm/yr made by Wilson (1985) for Yucca Mountain.

Data concerning transpiration by xerophytes is lacking for the area of study. Sammis and Gay (1979) estimated the transpiration by a large creosote bush to be 5 to 8 percent of precipitation. Since these plants do not draw water from the water table, it seems that their primary effect is to reduce infiltration from the soil zone to the unsaturated zone. This may be an important factor in the budget.

Phreatophytic transpiration, on the other hand, has been relatively well studied, and some data exist for the study area that can be used for quantification of this parameter; for example, some areas of phreatophytic growth are identified in the spring inventory in Section 3.5.1 and in Section 3.6. Included in the studies of phreatophytes are several attempts at formulating a general method for estimating transpiration based on empirical data (Decker and Wein, 1957; Hughes and McDonald, 1966; Robinson, 1970) and several methods for calculating evapotranspiration using meteorological or hydrologic data (Rantz, 1968; Hanson and Dawdy, 1976). Proper estimation of the rate of transpiration from the various plant types will depend on the availability of information detailing areal distributions and densities of vegetation throughout the study area. Several studies have surveyed the biota in the area of the NTS (O'Farrell and Emery, 1976; Collins et al., 1982; O'Farrell and Collins, 1983; O'Farrell and Collins, 1984; Collins and O'Farrell, 1985); however, additional information will be obtained during site characterization (Section 8.3.1.2.1).

The great depth to the water table in most of the study area all but eliminates the importance of evaporation from the capillary fringe over large portions of the area. This form of discharge is different from evaporation from soil in that moisture is lost from the transition zone between the saturated and unsaturated zones (i.e., the capillary fringe) rather than directly from the zone of saturation or from the upper soil zone that may have been wetted by recent precipitation. Both forms of discharge may occur in areas where the water table is near the surface, such as Alkali Flat and possibly areas of perched water, where it could be a significant factor. Ripple et al. (1972) include a discussion of this process and a method for estimation of its rate.

The presence of a well-developed calcic horizon may act as an infiltration barrier and may retard percolation below the horizon. Infiltration could accumulate above such a horizon, thereby allowing evaporation from the soil and capillary fringe and transpiration by plants to discharge nearly all of the precipitation entering that area. Such calcic horizons occur commonly throughout the region as well as at Yucca Mountain (Swadley and Hoover, 1983; Swadley et al., 1984; Taylor and Shroba, 1986; Rosholt et al., 1985). (A further discussion is given in Section 1.2.) The influence of the calcic horizon will be evaluated in the infiltration studies discussed in Section 8.3.1.2.2.

Evaporation from those surface-water bodies identified in Section 3.1 can be estimated on the basis of their surface area and pan evaporation data for the area. Pan evaporation for the area is estimated to be over 250 cm/yr according to Nichols (1986) and Dudley and Larson (1976). However, this figure is the potential evaporation. The volume of actual evaporation is expected to be relatively low due to the very limited availability of surface water bodies in the area. Nonetheless, this form of discharge is believed to be an important factor in the water budget. Information concerning the surface areas of these bodies is lacking and plans to obtain this information during site characterization are described in Section 8.3.1.2. Estimates of evaporation during periods of inundation due to flooding could also be made based on the area and period of inundation and pan evaporation. Much of the data necessary for these calculations are available in the form of topographic maps and previous and planned flood studies. Plans for these activities are discussed in Section 8.3.1.2.1.

Planned studies at Franklin Lake playa (Section 8.3.1.2.1) will provide data related to total evapotranspiration. Several techniques will be used to provide information on discharge rates and quantities, soil-moisture, phreatophyte distribution, evapotranspiration rates, and other parameters.

In addition to evapotranspiration from natural sources, quantification of discharge through human-related activities is planned (Section 8.3.1.16). Water use projections are available for agriculture, livestock, and domestic users in publications such as Water for Nevada (Office of the State Engineer, 1974). Discussions of ground-water use are included in Section 3.8.

In summary, studies that have been performed to date indicate that all of the components of ground-water discharge are significant when compared with the estimated recharge rates. In general, there is a paucity of site specific data, and meaningful estimates of these components cannot be made at this time. Additional studies, which will provide the necessary data to quantify these parameters, are included in the site characterization plans discussed in Section 8.3.1.2.

3.5.1 SPRINGS, SEEPS, AND PHREATOPHYTE AREAS

Springs can be classified on the basis of their ground-water source, (i.e., water-table springs and perched springs). Water-table springs discharge where the land surface intersects the water table. Perched springs, however, flow from the intersection of the land surface with a local ground-water body that is separated from the main saturated zone below by a zone of relatively lower permeability and an unsaturated zone.

Seeps are springs with very low discharge rates, commonly so low as to preclude measurement. Similar to springs, seeps may be classified according to their ground-water source.

An inventory of springs, seeps, and phreatophyte areas in the hydrogeologic study area has been compiled and is presented in Table 3-5. This list is based on data from Thordarson and Robinson (1971), Malmberg and Eakin (1962), Pistrang and Kunkel (1964), Schoff and Moore (1964), Miller (1977), Winograd and Thordarson (1975), Dudley and Larson (1976), White (1979), and Waddell et al. (1984). The springs are grouped according to basin boundaries (Sections 3.7.1 and 3.7.2). Springs are located using latitude and longitude coordinates to the nearest second, when available, and township and range designation. Perched springs are noted in the comments column. Hydrostratigraphic unit information, when available, is derived from the reference(s) listed in the reference column.

Also included in the spring inventory are some areas of phreatophytic growth. These areas are responsible for considerable amounts of ground-water discharge through evapotranspiration. Playas and alkali flats have not been included in the spring inventory because of the lack of data concerning quantities of discharge and the locations of many of these areas. As stated previously, such hydrologic conditions do not occur within the immediate vicinity of Yucca Mountain. However, they are believed to be important sites for ground-water discharge and are planned to be identified and mapped during site characterization (Section 8.3.1.2.1).

Areas of spring discharge are grouped into several distinct locations within the hydrogeologic study area. The primary areas are southern Oasis Valley (north of Beatty), Ash Meadows, Furnace Creek Wash (at Death Valley National Monument), and an area of minor ground-water discharge north and west of Yucca Flat. (A further discussion is given in Section 3.7.1.) The first three locations are situated at the discharge areas of the Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek Ranch subbasins, respectively, shown on Figure 3-7 (3.7.1.1). The springs located within these three areas are primarily water-table springs and are associated with the regional ground-water flow (Sections 3.7.1 and 3.7.2). Several springs in the Oasis Valley discharge area, however, may flow from a perched water table located near the contact of the Tertiary volcanic beds and the Quaternary alluvium of the area (Waddell et al., 1984). Most of the springs that flow in the area north and west of Yucca Flat are perched springs (Schoff and Moore, 1964; Winograd and Thordarson, 1975). Table 3-6 groups the springs listed in the inventory that include an individual discharge rate, by magnitude of their discharge. Section 3.7 describes the regional flow system and includes information regarding the springs and areas of discharge discussed above.

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 1 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
					ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (CALIFORNIA)								
36 26 40	116 49 50	27N/01E-23R1	Travertine		400	122	305	19.2	92	33	ND	T&R, 71 P&K, 64	
36 26 30	116 49 40	27N/01E-26A2	Travertine		320	98	220	13.9	92	33	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 50	27N/01E-26A5	Travertine		320	98	ND[d]	ND	95	35	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 50	27N/01E-26A6	Travertine		330	100	270	17.0	94	34	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 50	27N/01E-26A7	Travertine		330	100	ND	ND	85	29	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 40	27N/01E-26A1	Travertine		330	100	103	6.5	82	28	Irrigation	T&R, 71 P&K, 64	Discharge value includes discharge from the two springs listed below
36 26 30	116 49 40	27N/01E-25D2	Travertine		400	122	ND	ND	92	33	Irrigation	T&R, 71 P&K, 64	Seep
36 26 30	116 49 40	27N/01E-25D1	Travertine		400	122	ND	ND	92	33	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 50	27N/01E-26A3	Travertine		320	98	0.4	0.025	89	32	Irrigation	T&R, 71 P&K, 64	
36 26 30	116 49 50	27N/01E-26A4	Travertine		320	98	4	0.25	94	34	Irrigation	T&R, 71 P&K, 64	
36 30 30	116 49 10	28N/01E-36K1	Nevares		920	280	ND	ND	69	21	Domestic Public supply	M, 77 P&K, 64	Seep
36 30 30	116 49 40	28N/01E-36M2	Nevares		745	227	ND	ND	84	29	Domestic Public supply	M, 77 P&K, 64	
36 30 30	116 49 40	28N/01E-36M1	Nevares		720	220	31	1.96	78	26	Domestic Public supply	M, 77 P&K, 64	
36 30 40	116 49 10	28N/01E-36G2	Nevares		896	273	22	1.39	102	39	Domestic Public supply	M, 77 P&K, 64	

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 2 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
					ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (CALIFORNIA) (continued)								
ND	ND	28N/01E-36FS1			ND	ND	40	2.5	ND	ND	ND	M, 77 P.59	
36 30 40	116 49 10	28N/01E-36CS1	Nevares		937	286	269	16.97	104	40	Domestic Public supply	M, 77 P&K, 64	
36 29 40	116 51 20	27N/01E-03P1	Salt		0	0	4	0.25	73	23	Unused	P&K, 64	
36 29 40	116 51 20	27N/01E-03K1	Salt		100	30	ND	ND	ND	ND	NA[e]	P&K, 64	
36 27 10	116 51 00	27N/01E-22H1	Furnace Creek Inn Tunnel		50	15	148	9.34	92	33	Irrigation	P&K, 64	
36 26 30	116 49 40	27N/01E-26B1	South Travertine (Sump in Furnace Creek Wash)		280	85	566	35.7	92	33	Irrigation	M, 77 P&K, 64	
36 26 30	116 49 40	27N/01E-26B2	Buried tile in Furnace Creek Wash		250	76	200	12.62	ND	ND	Irrigation	P&K, 64	
36 26 40	116 49 50	27N/01E-23B1	Texas Spring (Tunnel)		380	116	224	14.1	91	33	Irrigation and public supply	P&K, 64	
		27N/01E-14N1			170	52	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-14P1			240	73	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-14Q1			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-23B2			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-23B3			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-23B4			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 27 10	116 50 20	27N/01E-23F1			160	49	4	0.25	80	27	ND	P&K, 64	
		27N/01E-23G1			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-23G2			400	122	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 3 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (CALIFORNIA) (continued)													
		27N/01E-23J1			410	125	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		27N/01E-23J2			410	125	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 27 00	116 50 10	27N/01E-23K1			410	125	NA	NA	ND	ND	NA	P&K, 64	Seep
36 27 00	116 50 10	27N/01E-23K2			400	122	4	0.25	ND	ND	ND	P&K, 64	
36 27 00	116 50 20	27N/01E-23L1			160	49	NA	NA	ND	ND	NA	P&K, 64	Seep
36 27 00	116 50 20	27N/01E-23L2			160	49	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 27 00	116 50 20	27N/01E-23L3			160	49	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 50 10	27N/01E-23Q1			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 50 10	27N/01E-23Q2			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 50 10	27N/01E-23Q3			320	98	4	0.25	72	22	ND	P&K, 64	
36 26 40	116 50 10	27N/01E-23Q4			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 50 10	27N/01E-23Q5			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 50 10	27N/01E-23Q6			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 40	116 49 50	27N/01E-23R2			410	125	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 26 40	116 49 50	27N/01E-23R3			410	125	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 26 40	116 49 40	27N/01E-24N1			400	122	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 30	116 50 10	27N/01E-26B4			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 26 30	116 50 10	27N/01E-26B5			320	98	NA	NA	ND	ND	NA	P&K, 64	Seep
36 30 00	116 51 00	27N/01E-3A1	Cow		200	61	18	1.14	81	27	Unused	P&K, 64	
		27N/01E-3B1			240	73	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		28N/01E-34M1			0	0	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 4 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
				ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (CALIFORNIA) (continued)									
36 30 10	116 51 50	28N/01E-34N1			10	3	NA	NA	74	23	NA	P&K, 64	Seep
36 30 10	116 51 50	28N/01E-34N2			80	24	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		28N/01E-34P1			100	30	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		28N/01E-35E1			380	116	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
		28N/01E-35G1			500	152	NA	NA	ND	ND	NA	P&K, 64	Phreatophyte area
36 30 30	116 50 20	28N/01E-35K1			520	158	NA	NA	76	24	Unused	P&K, 64	Seep
		28N/01E-35N1			380	115	4	0.25	78	26	NA	P&K, 64	
		25N/02E-13CS1	Lemonade	Volcanic Rock	3,800	1,160	<1	<0.06	54	12	ND	USGS Map 1:250,000 Death Valley M, 77	
		26N/02E-13FS1	Navel	Fanglomerate	2,080	634	ND	ND	73	23	ND	USGS Map 1:250,000 Death Valley M, 77	
36°39'	116° 51'	29N/01E-15			1,800	360	ND	ND	ND	ND	ND	USGS Map 1:250,000 Death Valley	
36°37'	116°48'	29N/02E-30			2,000	610	ND	ND	ND	ND	ND	USGS Map 1:250,000 Death Valley	
				ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (NEVADA)									
36 25 40	116 24 50	17S/49E-35d1	Ash Tree	ND	2,175	663	9	0.57	74	23	ND	T&R, 71 W&T, 75	
36 48 07	116 05 13	ND	Cane	Tertiary igneous	4,060	1,286	2	0.13	64	18	Unused	T&R, 71 W&T, 75	Perched (Wahmonie Formation) (W&T, 75)[c]
36 53 00	116 45 00	12S/47E-20bb1		ND	3,200	975	ND	ND	ND	ND	Irrigation	T&R, 71	
36 53 10	116 45 00	12S/47E-20bbb		ND	3,200	975	100	6.31	71	22	Irrigation	T&R, 71	

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 5 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
ALKALI FLAT-FURNACE CREEK RANCH SUBBASIN (NEVADA) (continued)													
36 56 21	116 16 14	ND	Topopah	Tertiary igneous	6,800	2,072	0.1	0.006	53	12	Unused	T&R, 71	Perched (S&M, 64)[c]
37 02 36	116 12 26	ND	Tippipah	Tertiary igneous	5,240	1,597	8	0.5	54	12	Unused	T&R, 71	Perched (S&M, 64)[c]
37 11 22	116 11 43	ND	Rainier	Tertiary igneous	6,240	1,902	0.1	0.006	67	19	Unused	T&R, 71	
37 26 30	116 06 00	06S/52E-10ad	Indian	Tertiary-Quaternary alluvium	6,685	2,038	2	0.13	49	9	Unused	T&R, 71	
37 30 40	116 05 20	05S/52E-14db	Cliff	Tertiary igneous	6,940	2,115	0.4	0.025	ND	ND	Unused	T&R, 71	
37 37 00	116 20 00	04S/50E-01dd		Tertiary igneous	6,550	1,996	0.1	0.006	ND	ND	Unused	T&R, 71	
36 45 30	116 15	ND	Pavits	Tertiary igneous	3,940	1,201	ND	ND	ND	ND	ND	T&R, 71	Perched (Piapi Canyon Group Wahmonie Formation) (W&T, 75)
36 18 50	116 18 40	19S/50E-02	Grapevine	ND	2,280	695	ND	ND	ND	ND	ND	T&R, 71 W&T, 75	
36 52 50	116 39 40	12S/48E-30	Specie	ND	4,400	1,341	ND	ND	ND	ND	ND	USGS Topographic Map, Death Valley 1:250,000 Quad	
OASIS VALLEY SUBBASIN													
36 55 10	116 44 40	12S/47E-05cda	Beatty	Tertiary volcanic	3,370	1,027	100	6.31	75	24	Public use	T&R, 71 W, 79	Not used (Gram, 1985)
36 56 30	116 43 40	11S/47E-33bac		ND	3,480	1,061	25	1.58	93	34	Domestic	T&R, 71	
36 56 40	116 47 40	11S/46E-26dcc	Lower Indian	Tertiary igneous	4,000	1,219	8	0.5	70	21	Stock	T&R, 71 M&E, 62	Perched (W et al., 84)[c];

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 6 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
						OASIS VALLEY SUBBASIN (continued)							
36 57 00	116 47 50	11S/46E-26ca-1	Middle Indian	Tertiary igneous	4,150	1,265	ND	ND	60	16	Municipal	T&R, 71 M&E, 62	Perched (W et al., 84)[c]; Beatty Municipal Supply (Gram, 1985)
36 57 10	116 48 20	11S/46E-26cbb-1	Upper Indian	Tertiary igneous	4,200	1,280	5	0.32	80	27	Municipal	T&R, 71 M&E, 62	Perched (W et al., 84)[c]; Beatty Municipal Supply (Gram, 1985)
36 57 00	116 43 00	11S/47E-28dac-1		Tertiary-Quaternary alluvium	3,480	1,061	35	2.21	70	21	Irrigation	T&R, 71	
36 57 30	116 43 10	11S/47E-28aa-2	Ute	Quaternary alluvium	3,540	1,109	25	1.58	70	21	Irrigation	T&R, 71 W, 79	
36 57 50	116 43 20	11S/47E-21dbb-2		Tertiary-Quaternary alluvium	3,550	1,082	37	2.33	79	26	Domestic	T&R, 71	
36 58 20	116 43 10	11S/47E-21aba-2	(Hicks?) (Bailey?)	Tertiary alluvium	3,600	1,097	ND	ND	106	41	Public	T&R, 71	
36 58 30	116 43 20	11S/47E-16dcd-2	Burro Hot	Tertiary igneous	3,600	1,097	5	0.32	98	37	Public	T&R, 71 M&E, 62	
36 58 30	116 43 20	11S/47E-16dcd-1	Burro Hot	Tertiary igneous	3,600	1,097	ND	ND	98	37	Domestic	T&R, 71	
36 59 10	116 45 30	11S/47E-18acb	Crystal	Tertiary igneous	3,960	1,207	2	0.13	75	24	Domestic	T&R, 71 M&E, 62	
36 59 30	116 42 50	11S/47E-10ccb		Tertiary-Quaternary alluvium	3,650	1,113	ND	ND	70	21	Stock	T&R, 71	
36 59 30	116 42 50	11S/47E-10ccb		Tertiary igneous	3,680	1,122	ND	ND	65	18	Domestic	T&R, 71	
36 59 40	116 42 30	11S/47E-10bdd		Tertiary igneous	3,800	1,158	49	3.09	75	24	Irrigation	T&R, 71	
37 00 00	116 42 20	11S/47E-10ab-1	Goss	Tertiary igneous	3,800	1,158	50	3.15	71	22	Irrigation	T&R, 71	

CONSULTATION DRAFT

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 7 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
						OASIS VALLEY SUBBASIN (continued)							
37 00 20	116 42 30	11S/47E-03cdb-1		Tertiary igneous	3,840	1,170	40	2.52	73	23	Irrigation	T&R, 71	
37 00 30	116 42 30	11S/47E-04cad		Tertiary-Quaternary alluvium	3,680	1,122	10	0.63	70	21	Irrigation	T&R, 71	
37 00 50	116 43 50	11S/47E-04bb-1		ND	3,720	1,134	7	0.44	65	18	Domestic	T&R, 71	
37 01 40	116 43 20	10S/47E-33abc		Tertiary igneous	3,680	1,122	255	16.09	72	22	Irrigation	T&R, 71	
37 01 50	116 45 10	10S/47E-31aab-1		Tertiary-Quaternary alluvium	3,840	1,170	11	0.69	67	19	Irrigation	T&R, 71	
37 02 00	116 45 20	10S/47E-30d-1		ND	3,850	1,173	25	1.58	58	14	Domestic	T&R, 71	
37 04 30	116 41 30	10S/47E-14bab		Tertiary-Quaternary alluvium	3,182	970	100	6.31	84	29	Irrigation	T&R, 71	
37 37 10	116 43 40	04S/47E-04ca	Antelope	Tertiary alluvium	6,220	1,896	0.4	0.025	53	12	Unused	T&R, 71	
36 59 40	116 51 20	11S/46E-08bdc	Mud	Tertiary-Quaternary alluvium	4,244	1,294	ND	ND	67	19	Stock	T&R, 71	
		12S/47E-20bb1		ND	ND	ND	ND	ND	ND	ND	Irrigation, domestic	M&E, 62	
		11S/47E-7dc1		ND	ND	ND	ND	ND	ND	ND	ND	M&E, 62	
		10S/47E-30d1		ND	ND	ND	25	1.58	58	14	Domestic, stock	M&E, 62	
		10S/47E-32dda		Quaternary alluvium	ND	ND	225	14.19	72	22	ND	W, 79	
						ASH MEADOWS SUBBASIN							
36 26 00	116 18 30	17S/50E-35a1		Lower carbonate aquifer	2,328	710	140	8.83	92	33	ND	T&R, 71 W&T, 75	Ash Meadows

CONSULTATION DRAFT

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 8 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
							ASH MEADOWS SUBBASIN (continued)						
36 26 10	116 18 50	17S/50E-35b1		Lower carbonate aquifer	2,305	703	17	1.07	83	28	ND	T&R, 71 W&T, 75	Ash Meadows
36 27 50	116 19 00	17S/50E-23b1	(Five Springs Area ?)	Lower carbonate aquifer	2,345	715	193	12.18	94	34	ND	T&R, 71 D&L, 76 W&T, 75	Ash Meadows
36 28 00	116 19 30	17S/50E-22a1	Longstreet	Lower carbonate aquifer	2,305	703	1,042	65.74	82	28	ND	T&R, 71 W&T, 75	Ash Meadows
36 28 50	116 19 30	17S/50E-15a1	Rogers	Lower carbonate aquifer	2,270	692	736	46.43	92	33	ND	T&R, 71 W&T, 75	Ash Meadows
36 29 20	116 20 10	17S/50E-10c1	Bell (Soda)	Lower carbonate aquifer	2,272	693	79	4.98	73	23	ND	T&R, 71 W&T, 75	Ash Meadows
36 29 20	116 20 30	17S/50E-09a1	Fairbanks	Lower carbonate aquifer	2,280	695	1,715	108.2	81	27	ND	T&R, 71 W&T, 75	Ash Meadows
		17S/50E-22ac	McGillivary	Lower carbonate aquifer	~2,300	701	See comments		ND	ND	ND	D&L, 76	Ash Meadows; flow reported in 1986 @ 155gpm; no flow observed in 1971; water level 5 ft below outlet
		17S/50E-35acc	Scruggs	Lower carbonate aquifer	~2,360	719	60	3.78	91	33	ND	D&L, 76	Ash Meadows
		17S/50E-35d1	School	Lower carbonate aquifer	~2,360	719	6	0.38	94	34	ND	D&L, 76	Ash Meadows
		18S/50E-01ca	Collins	Lower carbonate aquifer	~2,360	719	10	0.63	78	26	ND	D&L, 76	Ash Meadows

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 9 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
						ASH MEADOWS SUBBASIN (continued)							
		18S/50E-12dc	Sink	Lower carbonate aquifer	-2,260	689	See comments		ND	ND	ND	D&L, 76	Ash Meadows; flow observed @ 25 gpm in 1986; no flow observed in 1971; water level 3 ft below outlet
ND	ND	17S/50E-21ac	Cold	Lower carbonate aquifer	ND	ND	73	4.60	67	20	ND	D&L, 76	Ash Meadows
36 25 10	116 19 20	18S/50E-03a	Crystal Pool	Lower carbonate aquifer	2,197	670	2,820	177.91	91	33	ND	W&T, 75 T&R, 71	Ash Meadows
36 24 50	115 44 20	18S/55E-01d	Cold Creek	Tertiary-Quaternary alluvium	6,220	1,896	690	43.53	ND	ND	Domestic	T&R, 71	
36 25 00	115 45 50	18S/55E-02a	Willow	Tertiary-Quaternary alluvium	5,990	1,826	340	21.45	ND	ND	ND	T&R, 71	
36 26 40	115 55 40	17S/54E-29d	Big Timber	Cambrian sedimentary	6,720	2,048	ND	ND	ND	ND	ND	T&R, 71	
36 18 30	115 41 10	19S/56E-10c	Three	Cambrian limestone	8,700	2,652	21	1.32	ND	ND	ND	T&R, 71	Spring Mountains
36 19 10	115 40 40	19S/56E-03c	Scout Canyon	Ordovician limestone	8,470	2,582	11	0.69	ND	ND	ND	T&R, 71	Spring Mountains
36 21 30	116 16 20	18S/51E-30d	Last Chance	Lower carbonate aquifer	2,253	687	1	0.063	68	20	ND	T&R, 71 W&T, 75	Ash Meadows
36 21 50	116 15 40	18S/51E-29b		Lower carbonate aquifer	2,275	693	1	0.063	72	22	ND	T&R, 71 W&T, 75	Ash Meadows
36 21 50	116 16 10	18S/51E-30a1	Bole	Lower carbonate aquifer	2,245	684	12	0.76	72	22	ND	T&R, 71 W&T, 75	Ash Meadows

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 10 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
ASH MEADOWS SUBBASIN (continued)													
36 22 30	116 16 20	18S/51E-19a1	Big (Deep) (Ash Meadows)	Lower carbonate aquifer	2,239	682	1,036	65.36	83	28	ND	T&R, 71 W&T, 75	Ash Meadows
36 23 20	116 16 40	18S/51E-18b1	Jack Rabbit	Lower carbonate aquifer	2,270	692	587	37.03	82	28	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 00	116 18 00	18S/50E-12c1		Lower carbonate aquifer	2,245	684	11	0.69	80	27	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 00	116 18 10	18S/50E-11d3	Davis Ranch (Bradford)	Lower carbonate aquifer	2,242	683	30	1.89	72	22	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 18 10	18S/50E-11d2	Davis Ranch (Bradford)	Lower carbonate aquifer	2,242	683	5	0.32	74	23	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 00	116 18 10	18S/50E-11d1	Davis Ranch (Bradford)	Lower carbonate aquifer	2,242	683	397	25.05	77	25	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 16 10	18S/51E-07d1	King Pool (Point of Rock)	Lower carbonate aquifer	2,325	709	1,078	68.01	90	32	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 16 10	18S/51E-07d4	(Point of Rock)	Lower carbonate aquifer	2,325	709	19	1.20	93	34	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 16 10	18S/51E-07d3	Indian Rock (Point of Rock)	Lower carbonate aquifer	2,325	709	379	23.91	92	33	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 16 10	18S/51E-07d2	Indian Rock (Point of Rock)	Lower carbonate aquifer	2,325	709	22	1.83	92	33	ND	T&R, 71 W&T, 75	Ash Meadows
36 24 10	116 16 20	18S/51E-07d5	(Point of Rock)	Lower carbonate aquifer	2,310	704	2	0.13	93	34	ND	T&R, 71 W&T, 75	Ash Meadows

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 11 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
							ASH MEADOWS SUBBASIN (continued)						
36 25 30	116 17 30	17S/50E-36d1	Devils Hole	Lower carbonate aquifer	2,361	720	See comments		93	34	See comments	T&R, 71 D&L, 76 W&T, 75	Ash Meadows. No discharge as flow. <u>Cyprinodon diabolis</u> habitat
36 33 40	115 39 50	16S/56E-16b1	Indian	Tertiary-Quaternary alluvium	3,175	968	430	27.13	78	26	Domestic	T&R, 71	
36 34 30	115 43 40	16S/55E-11a	Cactus	Tertiary-Quaternary alluvium	3,238	987	0.5	0.031	ND	ND	Domestic	T&R, 71	
36 59 10	116 45 30	11S/57E	Quartz	ND	ND	ND	ND	ND	ND	ND	ND	T&R, 71	
37 10 09	116 10 07	ND	Captain Jack	Tertiary igneous	5,490	1,673	0.2	0.013	56	13	Unused	T&R, 71	Perched (S&M, 64)[c]
37 12 13	116 07 54	ND	Whiterock	Tertiary igneous	5,050	1,539	1.0	0.063	48	9	Unused	T&R, 71	Perched (S&M, 64)[c]
37 14 23	116 02 30	ND	Tubb	Tertiary igneous	5,190	1,582	ND	ND	52	11	Unused	T&R, 71	Perched (S&M, 64)[c]
37 14 41	116 04 24	ND	Oak	Tertiary igneous	5,800	1,768	0.1	0.0063	55	13	Unused	T&R, 71	Perched (S&M, 64)[c]
37 31 40	115 56 00	05S/54E-08bc	White Blotch	Tertiary igneous	5,960	1,817	0.2	0.013	42	6	Unused	T&R, 71	
36 27 50	115 57 40	17S/53E-24a	Gold	Cambrian sedimentary	6,780	2,067	ND	ND	ND	ND	ND	T&R, 71	
36 29 10	115 58 20	17S/53E-12c	Rock	Cambrian sedimentary	5,850	1,783	ND	ND	ND	ND	ND	T&R, 71	
36 29 10	115 59 00	17S/53E-11d	Jaybird	Cambrian sedimentary	6,280	1,914	ND	ND	ND	ND	ND	T&R, 71	
36 38 00	115 12 30	ND	Wiregrass	Ordovician dolomite	7,990	2,435	0.5	0.031	ND	ND	ND	T&R, 71	
36 38 50	115 13 50	ND	Pine	Ordovician dolomite	7,360	2,243	ND	ND	ND	ND	ND	T&R, 71	

Table 3-5. Springs, seeps, and phreatophyte areas in the hydrogeologic study area (page 12 of 12)

Latitude	Longitude	Township and range, spring location number	Name[a]	Aquifer[b]	Elevation ft	Elevation m	Discharge gpm	Discharge L/s	Temperature °F	Temperature °C	Use	Reference[c]	Comments
							ASH MEADOWS SUBBASIN (continued)						
36 39 30	115 13 10	ND	Canyon	Ordovician dolomite	8,020	2,444	ND	ND	ND	ND	ND	T&R, 71	
36 40 50	115 10 40	ND	Sawmill dolomite	Ordovician			8,140		2,481	ND	ND	T&R, 71	
36 41 30	115 12 30	ND	Basin dolomite	Ordovician			7,950		2,423	ND	ND	T&R, 71	
36 42 20	115 00 50	ND	Perkins	Ordovician dolomite			7,900		2,408	ND	ND	T&R, 71	
36 42 30	115 11 00	ND	Yellow Jacket	Ordovician dolomite			7,750		2,362	ND	ND	T&R, 71	
36 42 30	115 14 20	ND	Whiterock dolomite	Ordovician			5,930		1,807	ND	ND	T&R, 71	
36 42 50	115 10 50	ND	Shalecut dolomite	Ordovician			7,400		2,255	ND	ND	T&R, 71	
36 43 00	115 10 50	ND	Bootleg dolomite	Ordovician			7,200		2,194	ND	ND	T&R, 71	

[a]Blank means the area is not named.
[b]When the discharging aquifer could be determined, it is listed; otherwise only the lithology is shown. The main source of the ground water discharging in the Furnace Creek Ranch area is believed to be the lower carbonate aquifer (Waddell et al., 1984).
[c]P&K, 64 = Pistrang and Kunkel, 1964; M&E, 62 = Malmberg and Eakin, 1962; T&R, 71 = Thordarson and Robinson, 1971; W&T, 75 = Winograd and Thordarson, 1975; D&L, 76 = Dudley and Larson, 1976; M, 77 = Miller, 1977; W, 79 = White, 1979; W et al., 84 = Waddell et al., 1984; S&M, 64 = Schoff and Moore, 1964.
[d]ND = No data.
[e]NA = Not applicable.

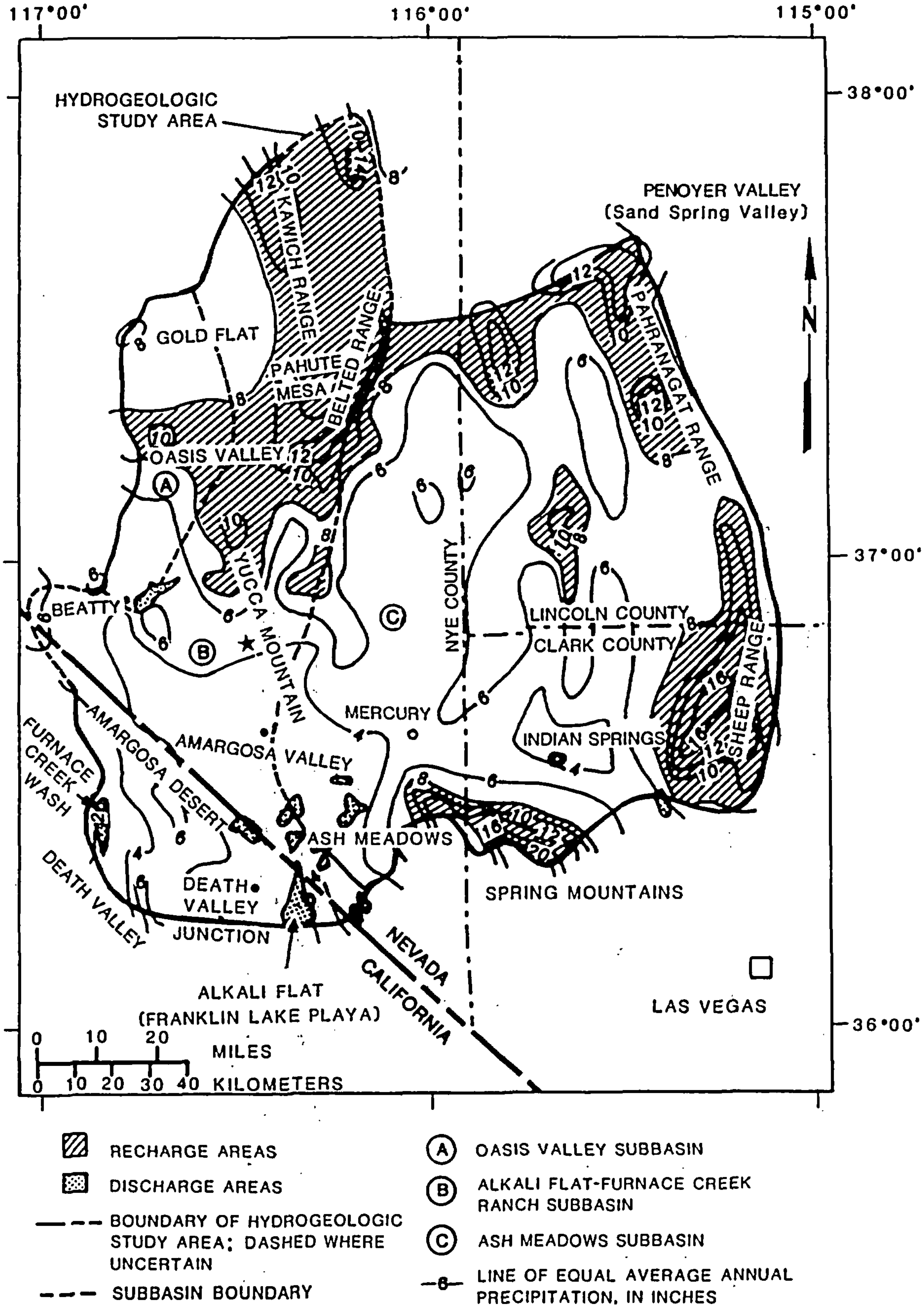

Figure 3-7. Hydrogeologic study area, showing precipitation, recharge areas, and discharge areas. Modified from Winograd and Thordarson (1975), Waddell (1982), and Waddell et al. (1984).

Table 3-6. Magnitude of springs in the hydrogeologic study area, based on Meinzer's[a] classification of spring discharge

Magnitude	Volume of discharge: English units	Volume of discharge: Metric units (L/s)	Number of springs in hydrogeologic study area
1	>100 ft^3/s	>2830	0
2	10-100 ft^3/s	283-2830	0
3	1-10 ft^3/s	28.3-283	9
4	100 gal/min to 1 ft^3/s	6.31-28.3	18
5	10-100 gal/min	0.631-6.31	27
6	1-10 gal/min	0.0631-0.631	21
7	1 pt/min to 1 gal/min	0.0079-0.0631	8
8	1 pt/min	<0.0079	4

[a]Adapted from Meinzer (1923).

3.5.2 POTENTIAL FOR CONTAMINATION OF SURFACE WATERS AND GROUND WATERS

No perennial surface waters exist on or near Yucca Mountain and very few areas of surface water are present within the hydrographic study area (Section 3.1). Ephemeral flow may occur as a result of high-intensity precipitation (Section 5.1). This storm runoff is commonly heavily laden with sediment and debris and may be used by vegetation and, to a minor extent, animals. However, this runoff is not used by humans for any purpose (DOE 1986; Section 3.2.3.3). The limited availability of surface water restricts the extent to which either plants or animals would be affected. Storm runoff would, most probably, only be affected in the immediate vicinity of the site. For this reason, modification of surface runoff, either in quantity or in chemical quality, is expected to have minimal, if any, impact on vegetation or wildlife. Other potential sources of surface runoff, such as dust-control spraying, are not expected to contribute to either surface or ground waters (DOE, 1986).

Ground water in the hydrogeologic study area is not expected to be contaminated or affected during site characterization activities. Controls over site characterization activities discussed below are considered sufficient to minimize the potential for any contamination of the ground water (DOE, 1986).

No contact is to be made with the water table at Yucca Mountain during site characterization except through exploratory boreholes. All water used for construction of the exploratory shaft will be tagged with a suitable tracer for identification purposes (Section 8.4.2) (Whitfield, 1985). Tracers will be used according to accepted procedures (Bedmar, 1983; Rao, 1983). Waste water from surface facilities and the exploratory shaft will be disposed of away from the repository block at either the hypalon-lined waste rock pile, lined evaporative ponds, or through septic tanks (Section 8.4.1). The exploratory shaft will be constructed using established mining techniques and a minimum of tagged water to prevent significant alteration of subsurface conditions (Section 8.4.2). Subsurface construction techniques will be designed to reduce the effects on the hydraulic characteristics of the rock (Sections 2.8.3 and 3.6.4). It is recognized that drilling fluids used in exploratory boreholes will have an effect on the chemical and hydraulic nature of the subsurface environment, including any water samples taken from that hole. These effects have been studied and can be quantified and controlled to some degree (NRC, 1983; Brobst and Buszka, 1986). If drilling mud is used in the drilling of boreholes, waste fluids would be disposed of on the rock pile or in the evaporative ponds (Section 8.4.1.2.5). Drilling mud may not be used where vacuum drilling is possible (Whitfield, 1985). This process will not only prevent contamination by drilling fluids but also allow for collection of uncontaminated rock and water samples and identification of perched-water zones. Exploratory boreholes will be sealed after the completion of down-hole testing and monitoring to minimize the potential for ground-water contamination through the boreholes (Sections 6.2.8.3 and 6.2.8.4).

3.6 REGIONAL HYDROGEOLOGIC RECONNAISSANCE OF CANDIDATE AREA AND SITE

The occurrence and movement of ground water in the vicinity of Yucca Mountain is, in part, controlled by the regional hydrogeologic system. The hydrogeologic units within this system have varied hydraulic characteristics and interrelationships and, hence, exert varying controls on ground-water flow rates and directions. In this section, the general characteristics of these units, their lateral extents, and their interrelationships are described.

The hydrogeologic study area is shown in Figure 3-2. The boundaries of this area are based upon a synthesis of many published interpretations and supporting geologic and climatologic studies as referenced in Chapters 1 and 5. The hydrogeologic study area includes three ground-water subbasins: Oasis Valley, Alkali Flat-Furnace Creek Ranch, and Ash Meadows, which are all part of the larger Death Valley ground-water basin (Waddell et al., 1984).

3.6.1 HYDROGEOLOGIC UNITS

The hydrogeologic study area falls within the Alluvial Basins Ground-water Region as described by Heath (1984). This region is characterized by alternating basins (valleys) and mountain ranges with unconsolidated alluvial sediments filling in the basins and with consolidated rock cropping out in the mountains and underlying the alluvial deposits in the basins. Individual basins may be hydraulically linked into regional flow systems or may be hydraulically isolated. The degree of hydraulic linkage or isolation of the hydrogeologic study area with adjacent subbasins or regional ground-water basins or flow systems, and the hydraulic interrelationships of individual subbasins within the study area itself are important considerations in defining and characterizing ground-water flow paths and velocities at Yucca Mountain. The areal distribution of the hydrogeologic units and their lithology and stratigraphy discussed in this section help to define the hydraulic communication on a regional scale and identify areas where additional information will clarify the overall characterization. Much of this information is summarized in Table 3-7. More detailed information about the geologic history and mode of occurrence of these units is provided in Chapter 1.

The existing data base on the areal extent, thickness, and interrelationships among the various geologic units within the hydrogeologic study area is sufficient to define regional hydrogeologic units and their general properties. No additional activities are designed to specifically refine the existing definition. However, the results of many of the planned activities will generate data that will help to further refine the level of knowledge about the regional hydrogeologic system.

3.6.1.1 Definition

A hydrogeologic unit (also referred to as a geohydrologic unit), as defined by Bates and Jackson (1980), is a geologic unit with consistent hydraulic properties such that the unit may be classified as an aquifer, confining layer (aquiclude or aquitard), or a combination of both, making up a framework for a reasonably distinct hydraulic system. The definition of a hydrogeologic unit is usually based on stratigraphic or lithologic characteristics, but as pointed out by Montazer and Wilson (1984), it may also be based upon structural considerations. In this section, the hydrogeologic units that occur in the saturated zone are defined and discussed. The hydrogeologic units recognized in the unsaturated zone at Yucca Mountain are described and discussed in Section 3.9.2.

3.6.1.2 Selection of units

The studies conducted by Winograd and Thordarson (1975) and additional assessments summarized by Waddell et al. (1984) identify the regional hydrogeologic units discussed in the following sections. These discussions are limited to those units that represent distinct hydraulic systems on a regional scale and do not necessarily correspond on a one-to-one basis with units discussed in Section 3.9.2 for the Yucca Mountain area. A generalized map showing the distribution of these units in the hydrogeologic study area is shown in Figure 3-8. As shown in Table 3-7, the regional hydrogeologic units in descending stratigraphic order are (1) the valley fill aquifer, (2) volcanic rock aquifers and aquitards, (3) the upper carbonate aquifer, (4) the upper clastic aquitard, (5) the lower carbonate aquifer, and (6) the lower clastic aquitard.

Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 1 of 7)

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Quaternary and Tertiary	Holocene, Pleistocene, and Pliocene deposits	Valley fill	Alluvial fan, fluvial, fanglomerate, lakebed, and mudflow ranges from 0.21 to 2.9 m/d	600	VALLEY FILL AQUIFER Transmissivity ranges from 10 to 400 m^2/d average coefficient of interstitial permeability ranges from 0.21 to 2.9 m/d. Interstitial porosity controls flow of water.
Tertiary	Pliocene	Basalt of Kiwi Mesa	Basalt flows, dense and vesicular	75	LAVA-FLOW AQUIFER Water movement controlled by primary and secondary fractures and possibly by rubble between intercrystalline porosity and conductivity negligible; estimated transmissivity ranges from 4.2 to 1,200 m^2/d; saturated only beneath east-central Jackass Flats.
		Rhyolite of Shoshone Mountain	Rhyolite flows	600	
		Basalt of Skull Mountain	Basalt flows	75	
	?[b]	Thirsty Canyon Tuff	Ash-flow tuff, partially to densely welded; trachytic lava flows	230	No corresponding hydrologic unit. Generally unsaturated; present beneath Black Mountain, northwestern part of the basin.
	Miocene[c]	Piapi Canyon Group, Timber Mountain Tuff, Ammonia Tank Member	Ash-flow tuff, moderately to densely welded; thin ash-fall tuff at base	75	WELDED AND BEDDED TUFF AQUIFER Water movement controlled by primary and secondary joints in densely welded part of ash-flow tuff; transmissivity ranges from 1 to 1,200 m^2/d; intercrystalline porosity and conductivity negligible; nonwelded part of ash-flow tuff, where present, has relatively high
		Piapi Canyon Group, Timber Mountain Tuff, Rainier Mesa Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff at base	175	

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Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 2 of 7)

System	Series	Stratigraphic unit			Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Tertiary	Miocene	Piapi Canyon Group		Tiva Canyon Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near here	90-100	interstitial porosity (35 to 50%) and modest permeability (0.08 m/d) and may act as a leaky aquitard; saturated only beneath deeper parts of Yucca, Frenchman, and Jackass flats.
			Paintbrush Tuff	Topopah Spring Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base	275	
				Bedded tuff (informal unit)	Ash-flow tuff and fluvially reworked tuff	300	Transmissivity ranges from 2 to 10 m^2/d; saturated only beneath structurally deepest parts of Yucca, Frenchman, and Jackass Flats; occurs locally below ash-flow tuff members of Paintbrush Tuff and below Grouse Canyon Member of Belted Range tuff.
		Wahmonie Formation			Lava-flow and interflow tuff and breccia; locally hydrothermally altered	1,200	<u>LAVA-FLOW AND TUFF AQUITARD</u> Water movement controlled by connected fractures; interstitial thermally altered porosity and permeability negligible; transmissivity estimated less than 6 m^2/d; contains minor perched water beneath foothills between Frenchman and Jackass flats.
					Ash-fall tuff, tuffaceous sandstone, and tuff breccia all interbedded; matrix commonly clayey or zeolitic	500	Transmissivity ranges from 1 to 3 m^2/d; interstitial porosity is as high as 40%, but interstitial permeability is negligible; (3×10^{-4} to 3×10^{-6} m/d); owing to poor hydraulic connection of

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Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 3 of 7)

System	Series	Stratigraphic unit		Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Tertiary	Miocene[c]	Salyer Formation		Breccia flow, lithic breccia, and tuff breccia, all interbedded with ash-fall tuff, sandstone, siltstone, claystone, matrix commonly clayey or zeolitic	600	fractures, interstitial conductivity probably controls regional ground-water movement; perches minor quantities of water beneath foothills flanking valleys; fully saturated only beneath structurally deepest parts of Yucca, Frenchman, and Jackass flats; Grouse Canyon and Tub Spring members of Belted Range Tuff may locally be aquifers in northern Yucca Flat.
		Belted Range Tuff	Grouse Canyon Member	Ash-flow tuff, densely welded	60	
			Tub Spring Member	Ash-flow tuff, nonwelded to welded	90	
		Local Informal Units		Ash-fall bedded tuff, nonwelded to semiwelded ash-flow tuff, tuffaceous sandstone. Siltsone, and claystone; all massively altered to zeolite or clay minerals; locally minor welded tuff near base; minor rhyolite and basalt	600	

Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 4 of 7)

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Tertiary	Miocene[c]	Rhyolite flows and tuffaceous beds of Calico Hills	Rhyolite, nonwelded and welded ash flow, ash-fall tuff, tuff breccia, tuffaceous sandstone; hydrothermally altered at Calico Hills; matrix of tuff and sandstone commonly clayey or zeolitic	600	<u>TUFF AQUIFER/AQUITARD</u> Rhyolite lavas and ash flows may be transmissive. Bedded tuffs may be zeolitized or argillized and less transmissive. Beneath Yucca Mountain the tuffaceous beds of Calico Hills are mostly unsaturated.
	Flat	Crater Bullfrog Tuff Prow Pass Member Member Tram Member	Ash-flow tuff, nonwelded to moderately welded, interbedded with ash-fall bedded tuff; matrix commonly clayey or	>600	<u>TUFF AQUIFER/AQUITARD</u> Transmissivity ranges from less than 0.1 to several hundred m^2/d. Interstitial hydraulic conductivity is small (8×10^{-4} to 3×10^{-1} m/d). At Yucca Mountain, unit commonly contains the water table.
		Lithic Ridge Tuff	Ash-flow tuff, partially to densely welded. Commonly argillized	300	<u>TUFF AQUITARD</u> Not well characterized. Transmissivity about 2×10^{-4} m^2/d. Interstitial hydraulic conductivity low (3×10^{-4} to 6×10^{-5} m/d).
Tertiary	Miocene (?) Oligocene (?)	Older tuffs and lavas beneath Yucca Mountain	Altered rhyolitic and quartz latitic lavas, and altered bedded and ash-flow tuffs	?	
	Miocene and Oligocene	Rocks of Pavits Spring	Tuffaceous sandstone and siltstone, claystone; fresh water limestone and conglomerate; minor gypsum; matrix commonly clayey, zeolitic, or calcerous	425	See Salyer Formation.

Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 5 of 7)

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Tertiary (continued)	Oligocene	Horse Spring Formation	Fresh-water limestone, conglomerate, tuff	300	See Salyer Formation
Cretaceous to Permian		Granitic stocks	Granodiorite and quartz monzonite in stocks, dikes and sills	--	(A MINOR PLUTONIC-ROCK AQUITARD) Complexly fractured but nearly impermeable.
Permian and Pennsylvanian		Tippipah Limestone	Limestone	1,100	UPPER CARBONATE AQUIFER Complexly fractured aquifer; transmissivity estimated in range from 10 to 1,250 m^2/d; intercrystalline porosity and permeability negligible, saturated only beneath western one-third of Yucca Flat.
Mississippain and Devonian		Eleana Formation	Argilliate, quartzite, conglomerate, limestone	2,400	UPPER CLASTIC AQUITARD Complexly fractured but nearly impermeable; transmissivity estimated less than 5 m^2/d; interstitial permeability negligible but owing to poor hydraulic connection of fractures probably controls ground-water movement; saturated only beneath western Yucca and Jackass Flats; interstitial porosity ranges from 2.0 to 18%.

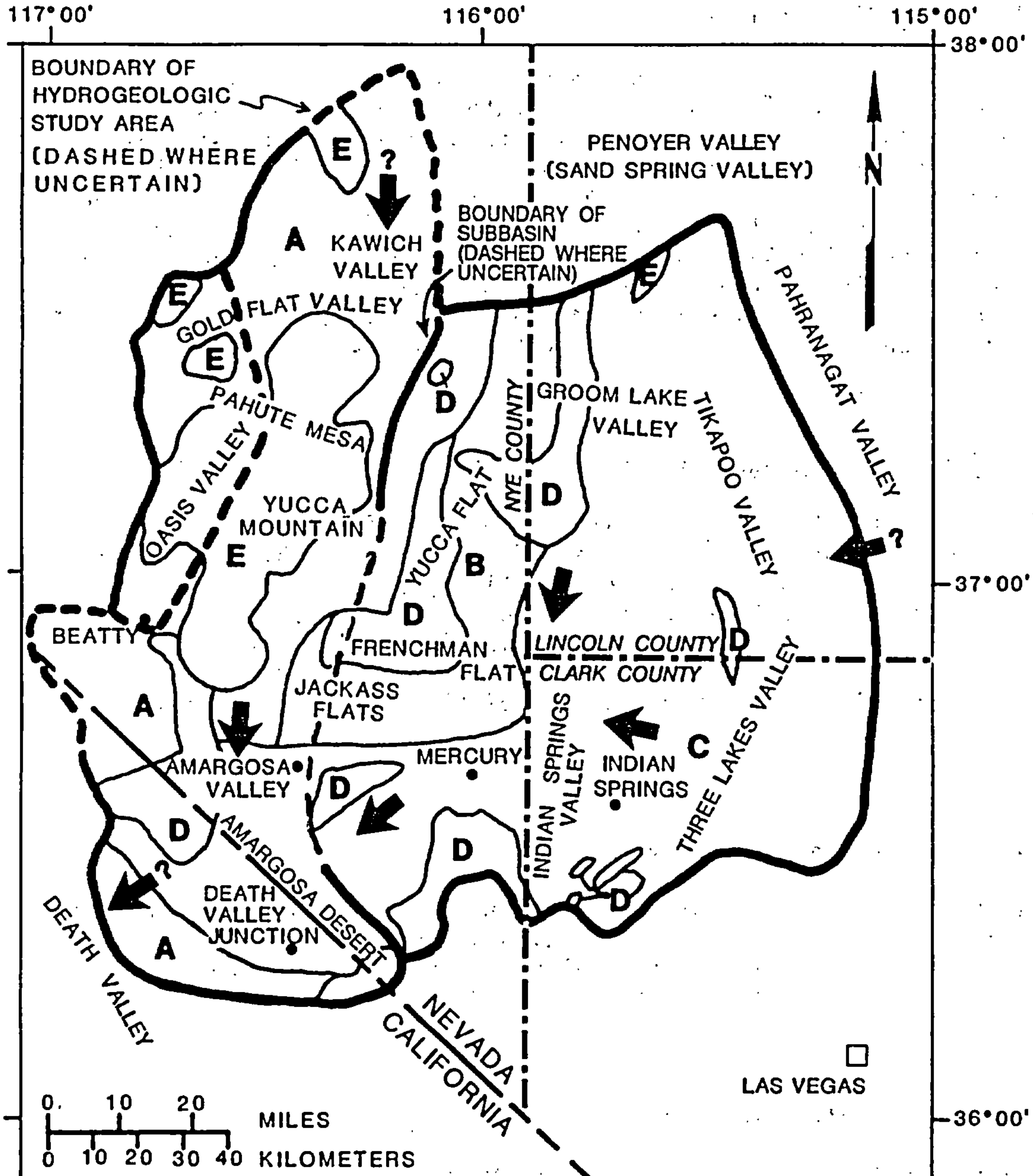
Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 6 of 7)

System	Series	Stratigraphic unit		Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Devonian	Upper	Devils Gate Limestone		Limestone, dolomite, minor quartzite	>425	LOWER CARBONATE AQUIFER Complexly fractured aquifer supplies major springs throughout eastern Nevada; transmissivity ranges from 10 to 10,000 m^2/d; intercrystalline porosity, 0.4 to 12%; intercrystalline hydraulic permeability, 9×10^{-7} to 4×10^{-3} m/d; solution caverns are present locally but regional ground-water movement is controlled by fracture transmissivity; saturated beneath much of study area.
	---?---					
		Middle		Nevada Formation	Dolomite	
Devonian and Silurian		Undifferentiated		Dolomite	430	
	Upper	Ely Springs Dolomite		Dolomite	90	
		Eureka Quartzite		Quartzite, minor limestone	100	
	Middle		Antelope Valley Limestone	Limestone and silty limestone	460	
Ordovician	---?---					
	Lower	Pogonip Group	Ninemile Formation	Claystone and limestone interbedded	100	
			Goodwin Limestone	Limestone	>275	
Cambrian	Upper	Nopah Formation				
		Smoky Member		Dolomite, limestone	325	
		Halfpint Member		Limestone, dolomite, silty limestone	220	
		Dunderberg Shale Member		Shale, minor limestone	70	

Table 3-7. Relation of stratigraphic units to hydrogeologic units in the hydrogeologic study area[a] (page 7 of 7)

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (m)	Hydrogeologic unit (underlined) and hydrologic characteristics
Cambrian	Middle	Bonanza King Formation			
		Banded Mountain Member	Limestone, dolomite, minor siltstone	750	
		Papoose Lake Member	Limestone, dolomite, minor siltstone	650	
		Carrara Formation	Siltstone, limestone, interbedded (upper part predominantly limestone; lower part predominantly siltstone	320 290	
	Lower				
Precambrian		Zabriskie Quartzite	Quartzite	70	LOWER CLASTIC AQUITARD Complexly fractured but nearly impermeable; supplies no major springs; transmissivity less than 10 m^2/d; interstitial porosity and permeability is negligible but probably controls ground-water movement owing to poor hydraulic connection of fractures; saturated beneath most of area; interstitial porosity 0.2 to 10%; interstitial hydraulic conductivity ranges from 3×10^{-4} to 4×10^{-6} m/d.
		Wood Canyon Formation	Quartzite, siltsone, shale minor dolomite	700	
		Stirling Quartzite	Quartzite, siltstone	1025	
		Johnnie Formation	Quartzite, sandstone, siltstone, minor limestone and dolomite	975	
		Noonday(?) Dolomite	Dolomite	--	

[a]Source: Waddell et al. (1984), which was modified from Winograd and Thordarson (1975).
[b]? indicates uncertainty.
[c]The three Miocene sequences occur in separate parts of the region. Age correlations between sequences are uncertain. They



GENERAL DIRECTION OF REGIONAL GROUND-WATER FLOW (QUESTION MARK INDICATES UNCERTAINTY)

A. VOLCANIC ROCK AQUIFERS AND AQUITARDS OVERLYING UPPER CLASTIC AQUITARD OR LOWER CARBONATE AQUIFER
B. VOLCANIC ROCK AQUIFERS AND AQUITARDS OVERLYING LOWER CARBONATE AQUIFER
C. LOWER CARBONATE AQUIFER
D. UPPER CLASTIC AQUITARD
E. VOLCANIC ROCK AQUIFERS AND AQUITARDS OF CALDERAS

NOTE: FOR CLARITY, VALLEY FILL AQUIFER NOT SHOWN

Figure 3-8. Generalized distribution of hydrogeologic units in the saturated zone of the region.

3.6.1.3 Valley fill aquifer

The valley fill aquifer is of Tertiary and Quaternary age and is composed of alluvial-fan, fluvial, fanglomerate, lakebed, and mudflow deposits (Table 3-7). The thickness and stratigraphic interrelationships of these deposits are highly variable reflecting varying depositional environments. Thicknesses more than 550 m occur in some areas, but because of the depths to water, areas where the alluvium is saturated are limited. Because of the limited thickness of saturated alluvium, this hydrogeologic unit is of minor importance in defining ground-water flow on a regional scale. The exception is beneath most of the Amargosa Desert, where the valley fill is present in saturated thicknesses sufficient to constitute an important aquifer.

3.6.1.4 Volcanic rock aquifers and aquitards

Volcanic rocks that occur in the region are of Tertiary age and consist of nonwelded to welded ash-flow tuffs and basaltic and rhyolitic flows (Table 3-7). Because of the complex stratigraphy of these volcanics, individual rock types are not differentiated on a regional scale. The aggregate thickness of this unit is not known, but in places it exceeds several thousand meters. These volcanics form the uppermost water-bearing unit throughout most of the northwestern part of the hydrogeologic study area (Figure 3-8).

3.6.1.5 Upper carbonate aquifer

The Tippipah Limestone of Pennsylvanian and Permian age constitutes the upper carbonate aquifer (Table 3-7). Although this unit is as much as 1,100 m thick, it is of minor regional hydrologic significance because it probably is saturated only beneath western Yucca Flat.

3.6.1.6 Upper clastic aquitard

The Eleana Formation of Devonian and Mississippian age constitutes the upper clastic aquitard. This unit comprises primarily argillite with minor quartzite and limestone (Table 3-7). The upper clastic aquitard acts as a confining unit separating the upper carbonate aquifer from the lower carbonate aquifer beneath western Yucca Flat and northern Jackass Flats. In these areas, the upper clastic aquitard is more than 2,400 m thick.

3.6.1.7 Lower carbonate aquifer

The lower carbonate aquifer comprises limestone in the upper part of the Cambrian Carrara Formation and the overlying limestones and dolomites of Cambrian through Devonian age (Table 3-7). The limestones of this aquifer occur extensively in the eastern part of the hydrogeologic study area and are a major regional aquifer. In places the thickness of this aquifer exceeds 4,700 m.

3.6.1.8 Lower clastic aquitard

Siltstone, quartzite, shale, and sandstone of Precambrian through early Cambrian age comprise the lower clastic aquitard (Table 3-7). Thicknesses greater than 3,000 m of these rocks occur within the hydrogeologic study area. The lower clastic aquitard is an important regional unit because it probably significantly affects the distribution of hydraulic potential and the locations of ground-water discharge areas.

3.6.1.9 Spatial relationships of units

The spatial relationships of these units are primarily a result of the depositional history of the sedimentary rocks, the volcanic history of the area, and the complex structural evolution of the region. The rocks of the lower clastic aquitard and lower carbonate aquifer were deposited in a miogeocline in thick accumulations (Stewart and Poole, 1974). In middle Paleozoic time, a sequence composed of generally poor water-transmitting siliceous clastic rocks was thrust eastward about 150 km along the Roberts Mountains thrust. These rocks now overlie a sequence composed mostly of relatively soluble, water-transmitting carbonate rocks. Subsequent deposition of rocks forming the upper clastic aquitard and upper carbonate aquifer occurred, followed by additional structural activity. In the Tertiary, volcanic activity resulted in the formation of the volcanic rock aquifers and aquitards. More recent geomorphic processes resulted in the deposition of the valley fill aquifer and unsaturated valley fill over these rocks.

3.6.2 RELATIONSHIP AMONG HYDROGEOLOGIC UNITS

Because of the complex geologic history, ground-water flow relationships within and between the hydrogeologic units are also complex. Data are sufficient to allow generalizations of these relationships. The valley fill aquifer lacks lateral continuity. Ground water in the valley fill aquifer in the northeastern part of the hydrogeologic study area has a downward component of flow resulting in leakage of ground water into the underlying aquifers (Winograd and Thordarson, 1975).

Where several aquifers and aquitards are present, such as beneath Yucca Flat, hydraulic heads generally decrease with depth indicating downward leakage toward the lower carbonate aquifer (Winograd and Thordarson, 1975). Near Yucca Mountain, on the other hand, the reverse is true, and an upward hydraulic gradient occurs (Waddell et al., 1984). The upward gradient in this area is discussed in Section 3.9.3.

Although both upward and downward components of interunit flow occur, the primary component of ground-water flow, in a regional scale, is lateral. With respect to detailed characterization of the Yucca Mountain area, knowledge of the distribution of vertical hydraulic gradients is important. However, a detailed definition of localized vertical gradients over the entire hydrogeologic study area is unnecessary in a regional reconnaissance. Because only limited data are presently available, data obtained during more specific studies will be used to help quantify the magnitude and rate of interunit flow (Section 8.3.1.2.1.2).

3.6.3 POTENTIOMETRIC LEVELS

The generalized locations of ground-water monitoring wells and the regional distribution of potentiometric levels referenced to mean sea level (msl) are presented in Figure 3-9. The distribution of wells provides an adequate data base for the general definition of the regional potentiometric surface. Sources of potentiometric data include Eakin et al. (1963), Malmberg (1967), Mifflin (1968), Winograd and Thordarson (1968), Rush (1970), Thordarson and Robinson (1971), Naff et al. (1974), Winograd and Thordarson (1975), Miller (1977), Harrill (1982), Waddell (1982), Czarnecki and Waddell (1984), Robison (1984), and Robison (1986). Specific construction information for these wells is provided in the cited references and are not included here. The equipotential lines shown on Figure 3-9 are based upon composite water levels from several hydrogeologic units and are averages of the hydraulic heads in the boreholes.

The altitude of the potentiometric surface ranges from over 1,900 m above msl in the northernmost part of the hydrogeologic study area to below sea level in Death Valley. Steep hydraulic gradients occur in several areas, including north of Yucca Mountain, near Death Valley, southeast of Mercury, and north of Yucca Flat. These steep gradients may be due to stratigraphic, structural, or hydraulic conditions, or to a combination of these conditions. Thermal conditions could also affect gradients, but preliminary analyses indicate that such effects probably are not significant influences on these steep gradients. The definition of areas of steep gradients and evaluation of the causes of these gradients are important considerations in determining ground-water flow paths and velocities. Additional syntheses and modeling of the regional hydrogeologic system will be performed as part of site characterization activities (Study 8.3.1.2.1.2). Two-dimensional and three-dimensional models of ground-water flow and sensitivity analyses performed during these studies will help to assess the relative importance of these steep gradients in the overall characterization of regional flow conditions.

The potentiometric data needed to establish temporal histories of variations in the potentiometric surface are available in selected areas, including Yucca Mountain, Amargosa Desert, Ash Meadows, and Franklin Lake playa. Collection of additional data is planned as part of the characterization of the regional ground-water flow system (Study 8.3.1.2.1.2). This data collection will include (1) regional potentiometric level studies to identify and compile additional data, (2) the expansion of the existing monitoring well network, and (3) local water-level monitoring.

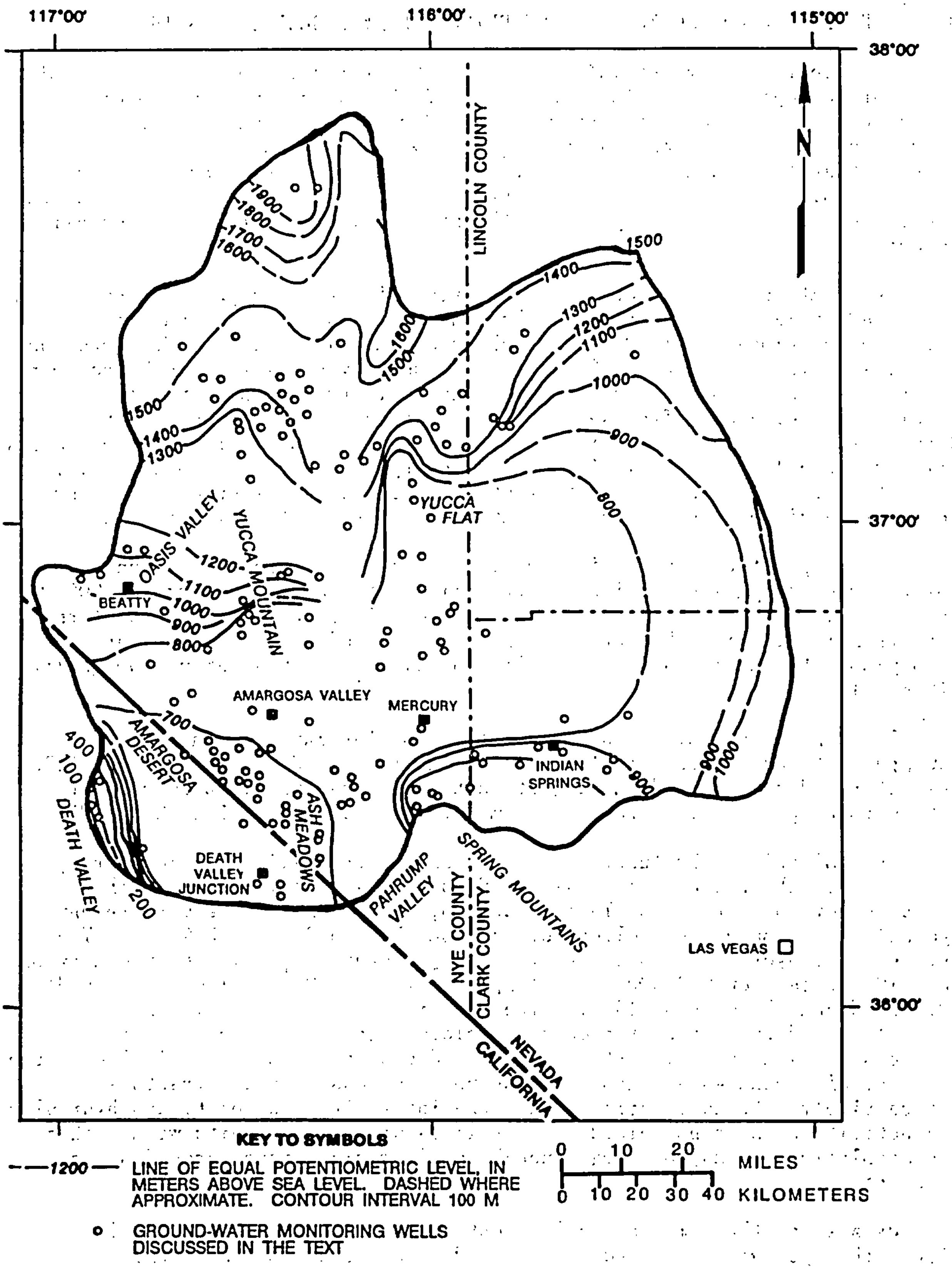


Figure 3-9. Potentiometric surface of the hydrogeologic study area (based on composite water levels). Modified from: Waddell et al. (1984).

3.6.4 HYDRAULIC CHARACTERISTICS OF PRINCIPAL HYDROGEOLOGIC UNITS

This section provides information on the hydraulic characteristics of the hydrogeologic units. The capability of the various regional hydrogeologic units to store and transmit ground water is a function of their hydraulic properties. Estimates of ground-water flow paths and velocities require that the hydraulic characteristics of each of the important hydrogeologic units be known. The principal hydraulic characteristics discussed are transmissivity, porosity, and both interstitial and fracture hydraulic conductivity.

Information on the hydraulic properties of the principal regional units is listed in Tables 3-7 and 3-8. These data are based on information published by Winograd (1962a,b), Blankennagel and Weir (1973), Winograd and Thordarson (1975), and Lin (1978). Transmissivity estimates are based upon aquifer testing. In many instances, transmissivity was estimated from specific-capacity data from wells. In the absence of other aquifer test data, these estimates are useful to provide minimum values for transmissivity (Winograd and Thordarson, 1975). The porosity and hydraulic conductivity estimates are based upon laboratory studies, including measurements of grain and bulk densities, and mercury-injection and water-saturation methods.

Based upon the results of these tests, the most transmissive unit is the lower carbonate aquifer, which has transmissivity values as large as 900,000 gpd/ft (10,000 m^2/d) (Winograd and Thordarson, 1975). All other aquifers have transmissivities that are at least an order of magnitude smaller. By comparison, the aquitards all have listed values less than about 800 gpd/ft (10 m^2/d).

The transmissivity of the valley-fill aquifer ranges from about 800 gpd/ft to 34,000 gpd/ft (10 to 400 m^2/d) (Winograd and Thordarson, 1975). The saturated thickness data suggest that these transmissivities reflect interstitial permeability ranging from 5 to 70 gpd/ft^2 (0.21 to 2.9 m/d).

The volcanic rocks function locally as either aquifers or aquitards, depending on the presence or absence of open, unsealed fractures. The character of these units at Yucca Mountain, where most of the more recent hydraulic data have been collected, is described in Section 3.9.2.2. The interstitial hydraulic conductivity of the volcanic units in the vicinity of the NTS ranges from 0.000007 to 4.1 gpd/ft^2 (2.8×10^{-7} to 1.6×10^{-1} m/d) (Winograd and Thordarson, 1975). The data indicate that the interstitial hydraulic conductivity of the densely welded zones of the volcanic rock aquifers and aquitards is extremely low and probably substantially limits the movement of ground water through these rocks unless they are fractured. Alternatively, the data indicate that the interstitial porosity and hydraulic conductivity of some nonwelded and partially welded tuff units within this hydrogeologic unit may be large enough to allow significant ground-water movement.

Because of the limited areal extent of the upper carbonate aquifer within the hydrogeologic study area, no data are available concerning its hydraulic properties. Similarly, data are limited on the hydraulic properties of the upper clastic aquitard. It has been inferred (Winograd and Thordarson, 1975) that the upper clastic aquitard is analogous to the lower

Table 3-8. Pumping-test data for aquifers in Nevada Test Site and vicinity[a] (page 1 of 4)

Well	Stratigraphic unit	Depth interval (m)	Thick-ness (m)	Estimated penetration of aquifer (%)	Hydraulic setting	Depth to static water level (m)	Specific capacity (L/s per meter of drawdown)[b]	Transmissivity (m^2/d) Estimated from specific capacity	Calculated from drawdown curve	Calculated from recovery curve	Remarks
79-69a	Carrara Formation	469-518	49	--[c]	Unconfined	469	110	1×10^4	--	--	Well 79-69a is 30 m northwest of well 79-69. During two pumping tests neither drawdown nor recovery could be measured owing to very high aquifer transmissivity and low pumping rates (3.7 and 13.4 L/s). Carrara Formation tapped by well is probably part of upper plate of low-angle thrust fault that crops out a few miles west of well.
79-69	Carrara Formation	469-503	34	--	Unconfined	469	1.28	75	(d)	(d)	Step-drawdown analysis indicates specific capacity of 2.4 (L/s)/m of drawdown and water entry chiefly from interval 490 495 m. Carrara Formation tapped by well is probably part of upper plate of low-angle thrust fault that crops out a few miles west of well.
67-73	Bonanza King Formation (Banded Mountain Member)	311-397	86	5	Confined	256	0.99	100	250	660	Step-drawdown analysis indicates specific capacity of 2.3 (L/s)/m of drawdown.
67-68	Bonanza King (?)[e] Formation	406-593	187		Confined						Step-drawdown analysis indicates specific capacity of 3.5 (L/s)/m of drawdown.
	Nopah Formation (?)	239-356	117	20	Unconfined	239	1.24	75	490	1,100	
66-75	Nopah Formation (Smoky Member)	225-454	224	10	Unconfined	225	0.93	50	140	330	Step-drawdown analysis indicates specific capacity of 2.2 (L/s)/m of drawdown.
88-66	Pogonip Group	777-1,042	266	10	Confined	626	0.08	9	16	66	Water yielded principally from interval 968-1,040 m.
75-73	Pogonip Group	336-565	229	10	Unconfined	336	0.14	7	47	--	--

Table 3-8. Pumping-test data for aquifers in Nevada Test Site and vicinity[a] (page 2 of 4)

Well	Stratigraphic unit	Depth interval (m)	Thickness (m)	Estimated penetration of aquifer (%)	Hydraulic setting	Depth to static water level (m)	Specific capacity (L/s per meter of drawdown)[b]	Transmissivity (m²/d) Estimated from specific capacity	Calculated from drawdown curve	Calculated from recovery curve	Remarks
73-66	Silurian (?) dolomite	956-1,036	80	<5	Confined	529	6.21[a]	740	--	--	Density changes in water column, due to anomalously high water temperature, completely masked water-level fluctuations due to pumping. Air-line measurements permitted approximation of specific capacity.
87-62	Devils Gate Limestone and Nevada Formation undifferentiated	1,128-1,280	172	<20	Confined	600	0.17	12	--	43	--
84 68d	Devonian (?) dolomite and calcareous quartzite	860-922	62	<5	Confined	596	0.08	9	30	--	--
					BEDDED-TUFF AQUIFER						
81-67	Bedded tuff (?) of Piapi Canyon Group	514-549	35	--	Confined	478	0.19	12	16	26	Aquifer is probably bedded tuff or nonwelded ash-flow tuff.
90-74	Bedded tuff (?) of Piapi Canyon Group	149-204	55	--	Unconfined (?)	149	0.08	2	--	--	Constant-rate pumping test not made; specific capacity based on measurements made after 90 min pumping; aquifer is probably bedded tuff or non-welded ash-flow tuff.
90-75	Bedded tuff (?) of Piapi Canyon Group	273-333	59	--	Unconfined (?)	273	0.12	5	--	--	Constant-rate pumping test not made; specific capacity reported after 30 min of pumping; aquifer is probably bedded tuff or nonwelded ash-flow tuff.

Table 3-8. Pumping-test data for aquifers in Nevada Test Site and vicinity[a] (page 3 of 4)

Well	Stratigraphic unit	Depth interval (m)	Thick-ness (m)	Estimated penetration of aquifer (%)	Hydraulic setting	Depth to static water level (m)	Specific capacity (L/s per meter of drawdown)[b]	Transmissivity (m^2/d): Estimated from specific capacity	Transmissivity (m^2/d): Calculated from drawdown curve	Transmissivity (m^2/d): Calculated from recovery curve	Remarks
					WELDED-TUFF AQUIFER						
75-58	Topopah Spring Member of Paintbrush Tuff	226-270	45	40	Confined (?)	226	11.6	1,240	See remarks	See remarks	Drawdown of 2.1 m measured with air line and test pressure gage in first 3 min of pumping test at rate of 24.4 L/s. Additional drawdown not detectable in subsequent 57 min of pumping test.
74-57	Topopah Spring Member of Paintbrush Tuff	283-444	161	100	Confined (?)	283	4.6	500	850	--	Step-drawdown analysis suggests considerable head losses at face of bore; losses are probably due to poor gun perforation of casing.
81-69	Topopah Spring Member of Paintbrush Tuff	459-511	51	100	Confined (?)	457	0.02	2.5	See remarks	0.6	Well tested by bailing.
					LAVA-FLOW AND WELDED-TUFF AQUIFERS						
74-61	Basalt of Kiwi Mesa	317-351	34	100	Unconfined	317	0.52	50	350	--	Combined test of lava-flow and welded-tuff aquifers. Measurements made with test pressure gage and air line.
	Topopah Spring Member of Paintbrush Tuff	351-465	55	45	Confined	--	--	--	--	--	
					VALLEY-FILL AQUIFER						
74-70b	Valley fill	210-366	156	60	Unconfined	210	0.35	12	30	31	Value of 21 m^2/d from recovery during 133-day shutdown; other values from 48-hour pumping test.

Table 3-8. Pumping-test data for aquifers in Nevada Test Site and vicinity[a] (page 4 of 4)

Well	Stratigraphic unit	Depth interval (m)	Thick-ness (m)	Estimated penetration of aquifer (%)	Hydraulic setting	Depth to static water level (m)	Specific capacity (L/s per meter of drawdown)[b]	Transmissivity (m²/d) Estimated from specific capacity	Calculated from drawdown curve	Calculated from recovery curve	Remarks
74-70a	Valley fill	208-274	66	15	Unconfined	208	0.83	37	95	136	--
75-72	Valley fill	218-265	48	--	Unconfined	218	0.27	10	--	--	Specific capacity and static water level reported by driller.
83-68	Valley fill	489-570	80	80-100	Unconfined	185	0.39	12	160	150	--
91-74	Valley fill	33-113	80	100	Unconfined	33	2.48	120	--	400	Specific capacity after about 211 hours of pumping; driller's log indicates mostly clay below 71.9 m.
91-74a	Valley fill	35-165	130	100	Unconfined	35	6.21	370	--	--	Specific capacity and static water level reported by driller; driller's log suggests chief aquifer in depth interval 34.7-61.0 m.

[a]Modified from Winograd and Thordarson (1975).
[b]Specific capacity computed at 100 min of pumping.
[c]-- indicates no data.
[d]Time drawdown curves in Winograd and Thordarson (1975) indicate a positive boundary of very high transmissivity at 35 min; the "zone" of high transmissivity probably is that tapped by adjacent well 76-69a.
[e](?) indicates data uncertainty.

clastic aquitard and probably has a transmissivity less than about 500 gpd/ft (6.0 m^2/d). No porosity data are available for either of these units.

Testing of the lower carbonate aquifer indicates that extremely high transmissivities occur. At well 79-69a (Table 3-8), completed in the Carrara Formation, a transmissivity of about 900,000 gpd/ft (1 x 10^4 m^2/d) was estimated on the basis of specific-capacity data. The total porosity of the lower carbonate aquifer ranges from 0.4 to 12 percent (Table 3-7), with an effective porosity ranging from 0.0 to 9.0 percent (Winograd and Thordarson, 1975).

Values of the interstitial porosity and hydraulic conductivity of the lower clastic aquitard given in Table 3-7 are based on analyses of 43 cores. Although restricted to cores from a single test hole, the data are considered representative of the lower clastic aquitard throughout the study area, because the borehole penetrated 1,072 m of the aquitard and the cores resemble examined outcrop specimens. The total porosity of this unit averages about 4 percent and the effective porosity is about 2 percent.

The transmissivity values summarized above are based upon analyses that assume porous media rather than fracture flow conditions and which presume that the ground-water flow in the saturated rocks satisfies Darcy's law (i.e., the flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path). For the purposes of regional characterization, such analyses are considered appropriate. However, their utility for calculation of ground-water flow paths and velocities over distances of a few kilometers or less is questionable. To determine the validity of the use of porous media solutions for flow through fractured media in the hydrogeologic study area, additional evaluations will be performed as summarized in Section 8.3.1.2.3.3. These evaluations will be performed as part of the assessment of regional hydrogeologic data needs in the saturated zone.

3.7 REGIONAL GROUND-WATER FLOW SYSTEM

This section describes the general ground-water flow and principal flow paths in the hydrogeologic study area and its component subbasins. The system hydrochemistry is presented, the ages of ground water are estimated, and the system paleohydrology is described. Information about the regional ground-water flow system is required to define ground-water flow paths, to estimate the effects of climatic changes on the water table altitude at the site, and to understand the ground-water flow system at the site.

Hydrologic conditions beneath Yucca Mountain are controlled in part by the regional ground-water flow system. Flow paths and water velocities beneath the site are determined by aquifer properties and hydraulic gradients. Because hydraulic gradients are affected by the regional distribution of permeability, and the locations and amounts of ground-water recharge and discharge, knowledge of the regional system is used for assessment of hydrologic conditions at Yucca Mountain.

3.7.1 IDENTIFICATION OF RECHARGE AND DISCHARGE AREAS

This section presents information on the (1) location of areas of ground-water recharge to and discharge from the ground-water system, (2) modes of recharge and discharge, (3) residence time of ground water, (4) bulk rates of ground-water flow for specific hydrogeologic units, and (5) surface-water ground-water interrelations.

3.7.1.1 Location of ground-water recharge and discharge areas

The recharge and discharge areas in the ground-water basin shown in Figure 3-7 are taken from Winograd and Thordarson (1975), Waddell (1982), and Waddell et al. (1984). The recharge areas shown are those areas of the basin that receive 200 mm or more average annual precipitation (Winograd and Thordarson, 1975) and are estimated to have relatively significant ground-water recharge, minor recharge probably occurs elsewhere in the basin, including Yucca Mountain. Surface-water runoff along major stream channels, such as Fortymile Wash, probably results in significant recharge, under both modern and post-pluvial conditions (Claassen, 1983; Czarnecki, 1985). Section 8.3.1.2.1 presents plans to evaluate the significance of this recharge. In addition, subsurface inflow probably occurs from the northeast, and may represent up to 58 percent of the total flow coming into the hydrogeologic study area (Czarnecki, 1985). The inflow across the northern and northeastern boundaries results from recharge in the higher areas to the north of the hydrogeologic study area. The northern boundary of the study area was arbitrarily located and is assumed to be a constant flow boundary rather than a no-flow boundary.

The principal areas of discharge are in the southern Amargosa Desert. Smaller, less significant areas are near Beatty, Indian Springs, and in Death Valley (Figure 3-7).

An additional potential source of inflow to the hydrogeologic study area is recharge from precipitation. Deep percolation from runoff originating from precipitation falling on the basin is included in the estimated recharge from precipitation.

3.7.1.2 Model of recharge and discharge

An empirical method of estimating average annual ground-water recharge from precipitation in desert regions was developed by Eakin et al. (1951). Recharge was estimated as a percentage of the average annual precipitation within an area. Geographic zones in which average precipitation ranges between specified limits were delineated on a map and a percentage of precipitation was assigned to each zone; this represented assumed average recharge from average annual precipitation in that zone. The degree of reliability of the estimate so obtained is related to the degree to which the values approximate actual precipitation, and the degree to which the assumed percentage represents actual percentage of recharge. Neither of these factors is known precisely enough to ensure a significant degree of reliability for any small area. Crosthwaite (1969) and Watson et al. (1976) compared this method to other methods of estimating recharge and concluded that it was suitable for obtaining an approximate estimate of recharge. This method has proved useful for reconnaissance estimates, and experience in using the method throughout Nevada and the desert areas of western Utah indicates that estimates probably are relatively close to actual long-term average annual recharge (Watson et al., 1976) in many large areas in these desert regions. However, the smaller the scale examined, the greater is the uncertainty of the method.

Claassen (1983) suggests that recharge to the valley-fill aquifer in the west-central Amargosa Desert, based on hydrochemical data, resulted primarily from overland snow-melt runoff during late Pleistocene time, in or near present-day stream channels such as Fortymile Wash. Today this area receives an average precipitation of less than 200 mm/yr. Infrequent, small, and localized modern floods still occur in these channels, and some recharge from them probably does occur.

In his estimates of recharge in the Alkali Flat-Furnace Creek Ranch ground-water subbasin, Czarnecki (1985) assumed that recharge associated with annual precipitation rates of less than 76 mm/yr was minor. Further, in his closing remarks, he states that "additional work is needed to document recharge mechanisms and rates, and to establish analytical expressions between precipitation rates and associated ground-water recharge rates." This is particularly true for channels such as Fortymile Wash on the east side of Yucca Mountain, where highly transmissive stream-channel sediments possibly focus recharge during flooding events. Little is known about the rate or distribution of deep infiltration there. Recharge through Fortymile Wash may affect the water-table altitude and gradient and flow-path directions beneath Yucca Mountain. Increased recharge through Fortymile Wash could result in a water table with higher altitudes and in modified gradients and ground-water flow rates (Czarnecki, 1985).

The amount of estimated average annual ground-water recharge from precipitation has been computed by Rush (1970) to be about 4.5×10^4 acre-ft (5.6×10^7 m^3) for a 16,000 km^2 area of the geohydrologic study area. This is equivalent to an average recharge rate of 3.5 mm/yr over the total area. Winograd and Friedman (1972) estimate that as much as 35 percent of the discharge at Ash Meadows in the southern Amargosa Desert (Figure 3-7, may be ground-water underflow from Pahranagat Valley. The springs at Ash Meadows flow about 2×10^7 m^3/yr (Walker and Eakin, 1963); therefore, the underflow from Pahranagat Valley may be on the order of 7×10^6 m^3/yr.

Although some uncertainty remains on the quantities and distributions of recharge over the region, the level of uncertainty does not appear significant in terms of affecting site specific analyses and interpretations for Yucca Mountain. Nonetheless, additional work is planned through regional modeling and water balance measurements as described in Section 8.3.1.2.1.

Ground-water discharge from the ground-water basin is by (1) spring flow, (2) evapotranspiration from phreatophyte areas where depths to ground water are less than about 15 m, and (3) evaporation from bare soil areas such as playas, where depth to ground water is less than about 5 m (Rush, 1970), and to a lesser extent, well withdrawals. At the major discharge areas in the basin (Figure 3-7), discharge is by evapotranspiration by phreatophytes and by natural springs that flow at the land-surface contact between transmissive and less-transmissive hydrogeologic units. The less-transmissive units act as barriers to ground-water flow, causing ground water to flow upward to land surface (Winograd and Thordarson, 1975). Major ground-water discharge is summarized in Table 3-9. Modeling studies by Waddell (1982) and Czarnecki and Waddell (1984) have shown recharge to be a highly sensitive element of regional flow models and additional studies are planned to determine discharge rates (Section 8.3.1.2.1).

Table 3-9. Major ground-water discharge in the hydrogeologic study area

Area (see Figure 3-9)	Nature of discharge	Estimated average discharge (m^3/yr)	Reference
Southern Amargosa Desert	Springs, evaporation, and evapotranspiration	3.0×10^7	Rush (1970), Walker and Eakin (1963),
Death Valley	Springs	6.3×10^6	Waddell (1982)
Near Beatty in Oasis Valley	Springs and evapotranspiration	2.7×10^6	Malmberg and Eakin (1962)
Indian Springs Valley	Springs	9.8×10^5	Maxey and Jameson (1948)
Total discharge		4.0×10^7	

Production wells contribute to the total discharge of the system. Data presented in Table 3-9 and tables in Section 3.8 indicate that well production may represent one third of the total discharge (total discharge from wells is 1.9×10^7 m^3/yr).

The total discharge shown in Table 3-9 does not include diversion from the study area by wells; well discharge is described in Section 3.8. Flow paths of ground water between recharge and discharge areas and the controls on the flow paths are discussed in Section 3.7.2.

3.7.1.3 Residence times of the ground water

Residence time of water in the hydrogeologic units is dependent on two factors: (1) ground-water velocities and (2) travel distances. Each of these factors is controlled by the highly complex hydrogeologic characteristics of the ground-water system.

A commonly used method for determining ground-water age is carbon-14 dating, although the presence of carbonate rocks along the flow path has an affect on the apparent ages determined (Tamers, 1967; Section 3.7.4). Claassen (1985) discusses limitations in determining ground-water ages and suggests various methods for correcting apparent ages of ground water. He also lists apparent ages of ground water near and at Yucca Mountain (9,100 to 17,000 yr before present) and in the Amargosa Desert (7,300 to 21,400 yr before present). Based on these apparent ages and length of flow paths, Claassen (1985) estimated ground-water velocities to be slower than 4 to 7 m/yr in the Amargosa Desert. Apparent carbon-14 ages from the tuff aquifers are probably not subject to much error, but apparent ages of the carbonate aquifers are assumed to require significant correction. Carbon-14 ground-water data and their interpretation for the Yucca Mountain vicinity are presented and discussed in more detail in Section 3.7.3.2, based on Claassen (1985) and Benson and McKinley (1985).

In a discussion of ground-water velocity, Winograd and Thordarson (1975) developed some estimates for residence and travel time for ground water beneath parts of the basin:

1. Beneath Yucca Flat, assuming an average saturated thickness of about 300 m and vertical movement, the time needed for a water particle to move from the top to the bottom of the tuff aquitard is about 6,000 to 2,000,000 yr, corresponding to velocities of 6×10^{-2} m/yr to 1.5×10^{-4} m/yr.

2. A carbon-14 date of water from the valley-fill aquifer beneath Frenchman Flat suggests that the age of the ground water in the tuff aquitard probably is in the range of several tens of thousands of years based on a sample with an apparent age of 13,000 yr. An age of several hundred thousand years is not beyond possibility for waters near the base of the tuff aquitard beneath Yucca or Frenchman flats, because vertical flow velocities through the underlying aquitard are likely to be very small, based on current rock-property data and recharge estimates.

3. Estimates of the velocity in the lower carbonate aquifer beneath central Yucca Flat range from about 6 to 600 mm/d, or from about 2 to 200 m/yr. Estimated average velocities beneath the Specter Range (15 km southwest of Mercury) are about 100 times larger than those for the lower carbonate aquifer beneath central Yucca Flat, or about 200 m to 20 km/yr and probably represent an upper limit of the ground-water velocities in the lower carbonate aquifer. Velocity estimates for the lower carbonate aquifer beneath Yucca Flat and the Specter Range principally reflect differences in the estimates of the volume of ground water flowing through each area used in estimating these ground-water velocities. These velocities were calculated by dividing the estimated flow through the aquifer by the carbonate aquifer cross-sectional area and the estimated effective porosity of 0.01 to 1 percent.

From wells in the area of Yucca Mountain, Waddell et al. (1984) report apparent carbon-14 ages of ground water ranging from 2,280 to 17,000 yr before present. The large variation in age is probably related to the travel distances from point of recharge. However, the extent to which mixing of differently aged ground waters may affect apparent ages in the hydrogeologic study area is unknown at present. Age of ground water beneath Yucca Mountain is more fully discussed in Section 3.9.1.3.

3.7.1.4 Bulk rates of ground-water flow

Bulk rates of ground-water flow for specific hydrogeologic units have not been determined; however, Waddell (1982), using a two-dimensional flow model, calculated unit fluxes for 12 locations, extending from Beatty to Death Valley; the values range from 7.0 m^2/yr to 2.8 x 10^3 m^2/yr. Also, Czarnecki and Waddell (1984) used a two-dimensional ground-water flow model of an area approximately equivalent to the Alkali Flat-Furnace Creek Ranch subbasin to calculate vertically integrated specific fluxes ranging from about 3.6 m^2/yr to 2.9 x 10^3 m^2/yr. Although only limited field data were available to calibrate the model, the calculated flux rates are consistent with total water balance data, gradients, and hydraulic conductivity and transmissivity data.

Additional modeling work is planned to estimate more accurately regional ground-water flux rates, as described in Section 8.3.1.2.1.

3.7.1.5 Surface-water ground-water interrelations

Runoff and the ponding of water generally result only from unusually intense precipitation or from rapid rates of snow melt. Because of rapid evaporation and commonly high potential for infiltration, those bodies of surface water do not persist in large areas for long periods of time. As a result, within most of the study area, perennial streams and lakes are absent or insignificant. The exceptions are the ground-water discharge areas, where springs support small pools of water and short perennial channels of streamflow. The flow commonly is used by man, evaporates, supports phreatophytes, or infiltrates back to the ground-water system where it continues to migrate in the subsurface. In the discharge areas, surface-water bodies generally are in hydraulic continuity with the saturated ground-water system. In recharge areas surface-water bodies are generally separated from the saturated zone by a thick unsaturated zone, so that a direct, saturated connection is not present.

Surface-water hydrology is discussed more completely in Section 3.1.

3.7.2 PRINCIPAL GROUND-WATER FLOW PATHS

As described in Section 3.7.1, ground-water movement is from recharge areas mostly in the northern and eastern part of the basin to the discharge areas of the western and southern part of the basin (Figure 3-10). Ground water flows generally southward or southwestward through most of the hydrogeologic study area; however, flow is westerly in the southeastern part

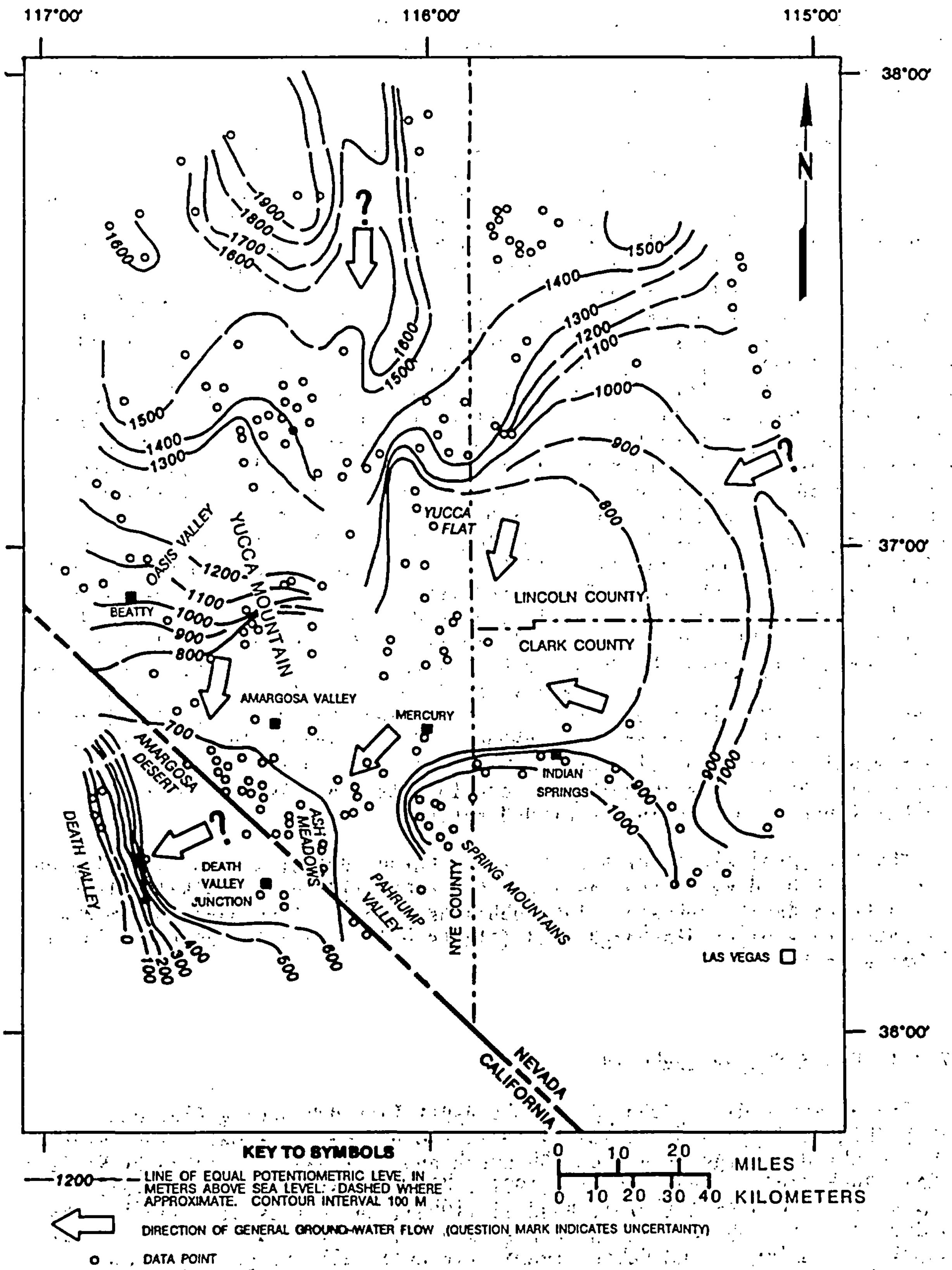


Figure 3-10. Regional ground-water flow paths. Modified from Waddell et al. (1984).

(Figure 3-10). Contour lines of the potentiometric surface are used only to determine the general direction of ground-water flow; local flow direction depends not only on the hydraulic gradient but also on anisotropy, of which little is known in the study area.

Temperature profiles in wells may be indicative of the local movement of ground water. Temperature variations with depth have been measured in selected boreholes in the hydrogeologic study area and surrounding area (Sass and Lachenbruch, 1982). Sass and Lachenbruch have interpreted a large area of anomalously low heat flow in eastern Nevada, extending into the northeastern part of the hydrogeologic study area. The area, called the Eureka Low, is interpreted to possibly have a downward component of ground-water flow on the order of a few millimeters per year, which is consistent with regional interpretations of recharge and discharge zones by Winograd and Thordarson (1975). The heat flow to land surface in the Eureka Low is less than 0.6 W/m^2. Elsewhere in the region, upward heat flow is higher and more typical of upward heat flow in the Great Basin (0.6 to 1.0 W/m^2, see Figure 1-52 in Chapter 1). Beneath Pahute Mesa, the reported heat flow to the land surface is unusually low (0.4 W/m^2); this may be the result of heat being transported out of the area by laterally flowing ground water in the upper 3 km of rock (Sass and Lachenbruch, 1982). That interpretation is consistent with interpretations based on geohydrologic data by Winograd and Thordarson (1975) and Blankennagel and Weir (1973). According to Sass and Lachenbruch (1982), based on an analysis of 60 boreholes on the NTS, thermal gradients indicate that the predominant vertical ground-water flow may be downward in the upper 2 to 3 km, but local upwellings may exist. However, only one of the 60 boreholes studied by Sass and Lachenbruch (1982) was completed in the manner required for a confident analysis of thermal effects of natural ground-water flow. This results in uncertainties regarding complications of local vertical flow (Sass and Lachenbruch, 1982). The influence of temperature variations and heat flow on the regional and site ground-water flow systems will be more thoroughly assessed in site characterization and related to other factors that influence ground-water flow.

The hydrogeologic study area includes three subbasins: Oasis Valley on the west, Ash Meadows on the east, and the centrally located Alkali Flat-Furnace Creek Ranch subbasin. The subbasins consist of recharge areas and flow paths to a major discharge area (Figure 3-7). Each is described in the following sections.

3.7.2.1 <u>Oasis Valley subbasin</u>

Ground-water discharges by evapotranspiration and spring flow near Beatty (Figure 3-7) in Oasis Valley (Malmberg and Eakin, 1962). The water flows to the discharge area from the north and northeast, as shown by Mifflin (1968), Rush (1970), Scott et al. (1971), Blankennagel and Weir (1973), Winograd and Thordarson (1975), Waddell (1982), Waddell et al. (1984). The boundary for the subbasin shown in Figure 3-7 is from Waddell et al. (1984). According to Malmberg and Eakin (1962), virtually all the ground-water discharge from Oasis Valley is by evapotranspiration and underflow to the Amargosa Desert. The estimated average annual evapotranspiration, as summarized in Section 3.7.1.2, is about 2.7×10^6 m^3/yr, derived from both spring flow and a shallow water table. The reported spring flow was about 2×10^6 m^3/yr (Table 3-5); and additional 4.9×10^5 m^3/yr was estimated by them to be ground-water outflow to the Amargosa Desert.

Flow paths are from the principal recharge areas, mostly in the central part of the subbasin (Figure 3-7), southward to the discharge area near Beatty. This flow is principally through volcanic-rock aquifers to the valley-fill aquifer underlying the discharge area. It is not known whether the lower carbonate aquifer is present at considerable depth below parts of the subbasin (Figure 3-7). According to Waddell (1982), the valley fill aquifer is underlain by the lower clastic aquitard. Some of the spring discharge is warm, suggesting deep circulation. Ground water not discharged by evapotranspiration flows southward through the valley fill aquifer, past an alluvium-filled narrows, and into the Amargosa Desert.

3.7.2.2 Ash Meadows subbasin

The Ash Meadows subbasin boundaries (Figure 3-7) are associated with mountain ranges and are generally ground-water divides (potentiometric highs) resulting from greater amounts of precipitation associated with higher land surface altitudes. Along the eastern side of the subbasin, ground water probably flows from Pahranagat Valley into Tikapoo Valley (Winograd and Thordarson, 1975). Winograd and Friedman (1972) estimated that 35 percent of the discharge at Ash Meadows is derived from Pahranagat Valley, based on differences in deuterium content of water from Pahranagat Valley, the Spring Mountains and Sheep Range, and Ash Meadows. Cowart (1979) suggested that the Pahranagat Valley and Spring Mountains are the only significant recharge areas for the Ash Meadows subbasin.

Loeltz (1960) speculated that the source of much of the Ash Meadows discharge was precipitation on the western slope of the Spring Mountains (Figure 3-7) following a flow path beneath Pahrump Valley. However, since 1960, more data have become available that are inconsistent with Loeltz's hypothesis. Based on potentiometric data, ground-water flow from Pahrump Valley to Ash Meadows may exist; however, the unnamed hills between these valleys are underlain by rocks of the lower clastic aquitard (Winograd and Thordarson, 1975; Harrill, 1982). Therefore, the amount of flow from Pahrump Valley to Ash Meadows, if any, probably is minor compared with other recharge and discharge fluxes in the subbasin. Naff et al. (1974) suggest that interbasin flow is improbable because the lower clastic aquitard crops out nearly continuously between Pahrump Valley and the spring discharge area. Head relations between Pahrump Valley and the Amargosa Desert also suggest a damming effect somewhere between.

Based on the above information, the boundary of the subbasin shown on Figure 3-7 is based primarily on the Winograd and Thordarson (1975) interpretation, which excluded the Spring Mountains and Pahrump Valley from the subbasin.

According to Winograd and Thordarson (1975), the flow paths are from the principal recharge area, mostly in the northern, eastern, and southern mountains of the subbasin, mostly westward to Ash Meadows in southern Amargosa

Desert where most of the ground water is discharged by many large springs. The ground water migrates downward to the lower carbonate aquifer from overlying aquifers, as described in Section 3.6 and earlier parts of Section 3.7. Flow paths are determined by hydraulic head differences in open fractures in the lower carbonate aquifer.

Flow in the Ash Meadows subbasin is primarily in the lower carbonate aquifer. Hydraulic gradients are low (commonly less than 0.0002) because of high transmissivities of the soluble, fractured lower carbonate aquifer (Winograd and Thordarson, 1975). Distribution of head and direction of flow are greatly affected by permeability differences among the hydrogeologic units (Winograd and Thordarson, 1968).

According to Winograd and Thordarson (1975) spring discharge of 8.7×10^5 m^3/yr occurs at Indian Springs. It is probably fed by upward leakage of ground water from the lower carbonate aquifer by way of the valley fill aquifer. A major hydraulic barrier probably exists in the vicinity of the spring that causes the ground water to flow upward.

From northern Yucca Flat to Ash Meadows, ground water apparently flows downward through the valley fill aquifer and volcanic-rock hydrogeologic units into the underlying carbonate aquifers beneath Yucca Flat. The potentiometric level is as much as 43 m lower in the carbonate aquifer than in the overlying units (Winograd and Thordarson, 1975; Doty and Thordarson, 1983). Ground water from the overlying aquifers is drained by the more transmissive underlying carbonate aquifers. These interpretations are based primarily on data from two well locations. It may be desirable to confirm the interpretations with one or more additional wells with multidepth head measurements. Plans for collecting additional data on this type are discussed in Section 8.3.1.2.

The lower carbonate aquifer transmits most of the water in the subbasin, but other lithologies are locally important. Northeast of the Ash Meadows spring line, the saturated thickness of the valley fill aquifer probably is more than 100 m. Beneath Frenchman Flat, both valley fill and volcanic aquifers are saturated beneath the structurally deepest parts of the valley. Most of the valley-fill aquifer beneath Yucca Flat is unsaturated (Winograd and Thordarson, 1975).

Discharge from springs at Ash Meadows is estimated to be 2×10^7 m^3/yr (Walker and Eakin, 1963; Dudley and Larson, 1976). An additional unknown amount of ground water flows to the Alkali Flat-Furnace Creek Ranch subbasin to the west, some of which discharges by evapotranspiration (Winograd and Thordarson , 1975). A normal fault, downthrown to the southwest (Healey and Miller, 1971), probably juxtaposes a low-permeability lakebed aquitard or eolian deposits on the downthrown side of the fault against the lower carbonate aquifer across the fault, forcing flow upward (Dudley and Larson, 1976). Discharge is from springs in alluvium downgradient (southwest) of the fault. Regional transmissivities of about 40,000 m^2/d have been calculated (Winograd and Thordarson, 1975) for the lower carbonate aquifer in the area northeast of Ash Meadows using estimated values for discharge, hydraulic gradient, and width of the aquifer; this figure is six to nine times greater than that determined from aquifer tests (Waddell, 1982).

3.7.2.3 Alkali Flat-Furnace Creek Ranch subbasin

Winograd and Thordarson (1975) suggest evidence that ground water flows from the south-central Amargosa Desert, through the lower carbonate aquifer, discharging at springs and seeps at Furnace Creek Ranch. Evidence supporting this belief consisted of the following: (1) proximity of spring discharge to the lower carbonate aquifer, (2) temperature relations of spring waters that are similar to those at Ash Meadows, and (3) the chemical quality of Travertine, Texas, and Nevares Springs are nearly identical. Ground water in the lower carbonate aquifer beneath the south-central Amargosa Desert may be derived from two sources--direct southwestward underflow from the Ash Meadows ground-water subbasin through the lower carbonate aquifer (assuming that the aquifer is extensive beneath the central Amargosa Desert), and downward leakage from the valley-fill aquifer beneath the central and south-central Amargosa Desert.

Discharge by natural processes in the Amargosa Desert was estimated by Walker and Eakin (1963) to be about 3 x 10^7 m^3/yr, based on mass-balance estimates, which they acknowledge are "crude"; ground-water outflow southward from the subbasin was estimated to be about 6.2 x 10^5 m^3/yr. Discharge near Furnace Creek Wash and Cottonball Marsh was estimated, based on some direct measurements of spring discharge and mapping of seeps in alluvium, to be about 6.3 x 10^6 m^3/yr (Hunt et al., 1966). Total flux (volumetric flow rate) in the Alkali Flat-Furnace Creek Ranch subbasin, not including the discharge in the Oasis Valley and Ash Meadows subbasins, is estimated to be about 2 x 10^7 m^3/yr (Waddell, 1982). Waddell (1982) used a parameter-estimation model and determined that total flux into and out of the ground-water system is about 4.3 x 10^7 m^3/yr. This value is in good agreement with the total ground-water discharge of 4.0 x 10^7 m^3/yr indicated in Table 3-9.

Using a two-dimensional, finite-element, ground-water flow model, flow paths in the Alkali Flat-Furnace Creek Ranch subbasin were simulated by Czarnecki and Waddell (1984). The model was calibrated against measured head and boundary conditions. The results indicate that ground water flows predominantly southward from the Timber Mountain area in the northern section of the subbasin, beneath Crater Flat and the Amargosa Desert, toward the south and southwest, and to discharge areas located at Franklin Lake playa (Alkali Flat) and Furnace Creek Ranch in Death Valley. The model also indicates that additional minor components of ground water flow into the subbasin occur (1) from Calico Hills southward into Jackass Flats, (2) from Rock Valley into Jackass Flats, (3) from the western Amargosa Desert, and (4) from lateral recharge of ground water from the Ash Meadows subbasin. A summary of ground-water fluxes into and out of the hydrogeologic study area is shown in Table 3-10. Location of fluxes are shown in Section 3.9.3.3.

3.7.3 ISOTOPIC AND REGIONAL HYDROCHEMISTRY

This section describes the hydrochemical and isotopic nature of the ground water within the saturated zone in the hydrologic study area. Based on this data, estimates of ground-water age, origins, residence times, and travel times are presented. Discussions are provided regarding (1) the relative degree of circulation within the hydrogeologic units, (2) areas and

Table 3-10. Summary of fluxes into and out of the Alkali Flat-Furnace Creek Ranch subbasin[a,b]

Flux location	Rate[c] (m^3/d)	Percentage
Timber Mountain[d]	+ 31,446	57.3
Fortymile Wash	+ 22,140	40.3
Rock Valley	+ 1,079	2.0
Calico Hills	+ 158	0.3
Ash Meadows	+ 78	0.1
Western Amargosa Desert	+ 19	<0.01
Franklin Lake playa	- 35,600	64.8
Furnace Creek Ranch, Death Valley	- 19,320	35.2

[a]Source: Czarnecki and Waddell (1984).
[b]Flux calculated as a residual of the mass balance.
[c]+ indicates flow is into subbasin; - indicates flow is out of subbasin.
[d]Timber Mountain area was simulated as a constant head boundary in the model.

modes of recharge and discharge, and (3) the delineation of regional hydrochemical facies. Figure 1-10 (Section 1.2.1) provides the distribution of rock types in the region, Figure 3-11 shows the location of many of the regional physiographic features, and Figure 3-2 shows the hydrogeologic subbasins.

3.7.3.1 Regional hydrochemistry

The chemical composition of ground water in the region is principally determined by (1) reactions with carbonate and volcanic rocks or rock fragments; (2) concentration of dissolved chemicals by evaporation; (3) formation of smectites, zeolites, and evaporite minerals; and (4) mixing of waters of different compositions. Because of a scarcity of shales, quartzites and granites, reactions with these rocks do not produce significant changes in the chemical composition of water in the region.

3.7.3.1.1 Chemical composition of ground water

The chemical composition of the ground water within the hydrogeologic study area is discussed in terms of the tuffaceous, lower carbonate, and valley fill aquifers.

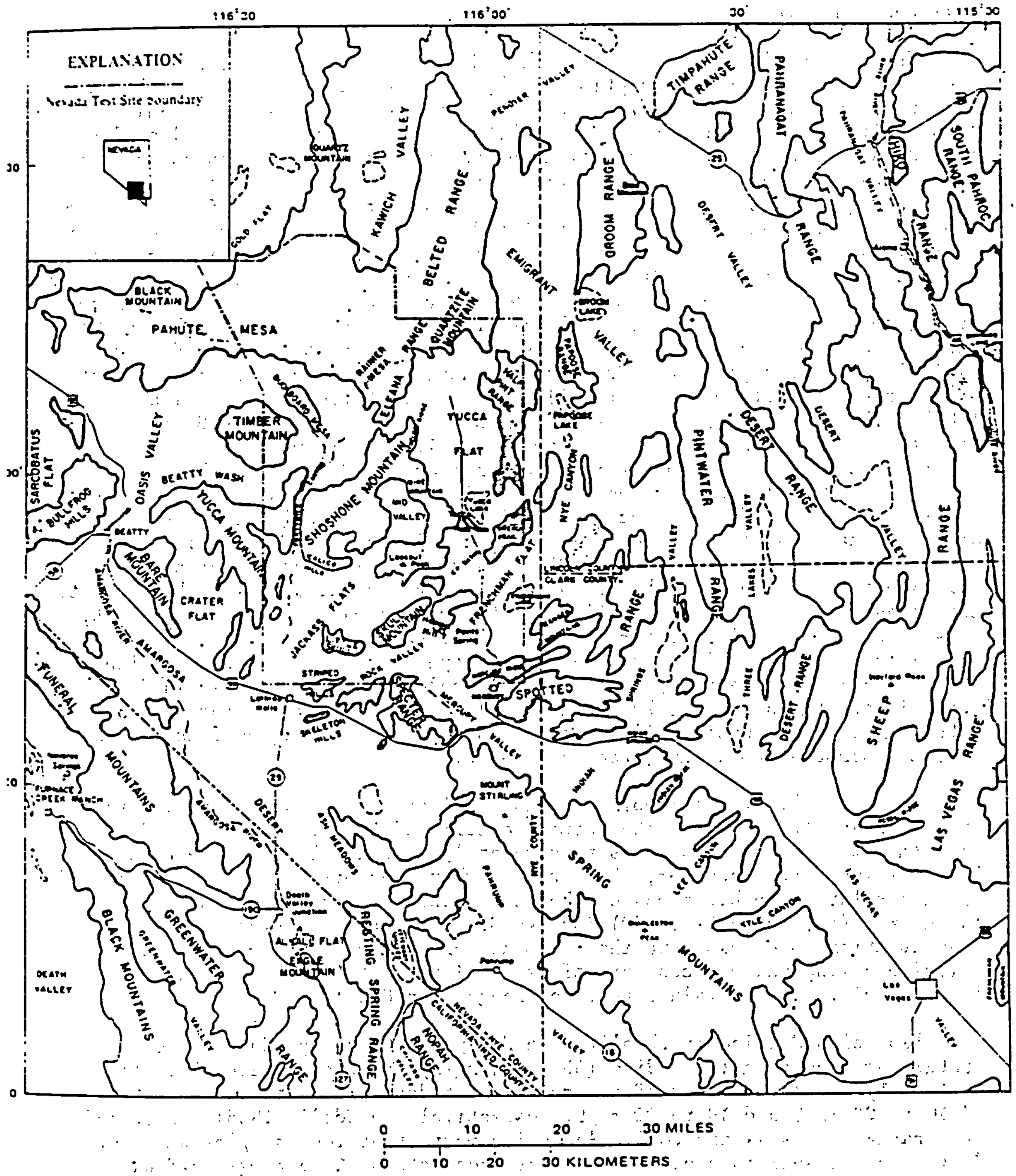


Figure 3-11. Location map showing regional physiographic features. Modified from Winograd and Thordarson (1975).

Tuffaceous aquifer

The sodium bicarbonate water, which dominates the tuffaceous rocks, evolves principally by dissolution of rhyolitic volcanic glass and subsequent precipitation of various zeolites and smectite clays (Claassen and White, 1979; White, 1979; Claassen, 1985). White (1979) presents chemical analyses for 13 water samples from the tuffaceous aquifer northwest of Yucca Mountain in the Oasis Valley. The major cations are sodium (50 to 200 mg/L), calcium (0 to 36 mg/L), potassium (1.5 to 11 mg/L) and magnesium (0 to 5 mg/L). The dominance of sodium ions can be attributed to the incongruent dissolution and hydrolysis of volcanic glass. White et al. (1980) report that incongruent dissolution in the tuff beds within Rainier Mesa preferentially releases sodium, calcium, and magnesium while retaining potassium. Calcium and magnesium show progressive depletion relative to sodium, not by ion exchange but due to the effective removal of bivalent ions as clinoptilolite and montmorillonite are precipitated. Greater percentages of sodium ion are associated with larger clinoptilolite:montmorillonite precipitation ratios (Claassen, 1985). The 13 water samples taken from the tuffaceous rocks in Oasis Valley show that the dominant anion is bicarbonate (115 to 330 mg/L), with sulfate, chloride, and fluoride present in concentrations of 0 to 217 mg/L, 14 to 3 mg/L, and 0 to 10 mg/L, respectively. Since the occurrence of carbonate minerals in the tuffaceous rocks is minimal, the principal source and control of bicarbonate is the reaction of dissolved soil-zone carbon dioxide with various mineral phases (White, 1979). Chloride is leached preferentially relative to fluoride from the fresh, previously unreacted, glass phase (White and Claassen, 1980). Aqueous silica (SiO_2) concentrations remain constant, showing supersaturation with respect to cristobalite and quartz, and saturation with respect to silica gel (amorphous hydrated SiO_2). Excess silica is removed from the aqueous systems as silica gel, which is observed in fractures in the tuffaceous rocks of Oasis Valley (White, 1979). For the 13 water samples from Oasis Valley, the pH is reported as ranging from 7.6 to 8.7, and temperatures range from 18 to 41°C.

White et al. (1980) report chemical analyses for 55 water samples from the pores and fractures of the saturated tuffs of Rainier Mesa. The data show that the fracture water is predominantly a sodium bicarbonate. The interstitial water, however, shows much higher concentrations of chloride and sulfate relative to bicarbonate. Relative concentrations are similar to those specified in White (1979) for the Oasis Valley. However, actual concentrations are less with the dominant ions sodium, bicarbonate, and chloride having maximum concentrations of 71 mg/L, 220 mg/L, and 62 mg/L, respectively. The pH values reported range from 6.8 to 8.3.

Two wells drilled in rhyolites in Fortymile Canyon produced water containing predominantly sodium (39 to 44 mg/L) and bicarbonate (54.9 to 56.7 mg/L). Calcium and sulfate are the next dominant, with concentrations of 10 to 23 mg/L and 19 to 22 mg/L, respectively (Waddell, 1985). Measured temperatures were 19 and 20°C. Waddell reports that four samples at varying depths in one well have dissolved oxygen contents of 2 to 5 mg/L and pH values of 7.1 to 7.6.

Benson and McKinley (1985) report the chemical composition of 25 water samples obtained from 14 test wells in and near the exploratory block (Section 3.9.1.3 and Chapter 4). Again, sodium and bicarbonate ions predominate. Temperatures range from 22 to 56°C, and pH values are 6.6 to 9.2. Although plots of relative cation and anion concentrations indicate a general description of sodium bicarbonate water, the ground water at Yucca Mountain is not chemically homogeneous. The differences in ionic composition among the wells is outlined and the authors conclude that ground water from the wells in the Yucca Mountain area has a significant degree of lateral and vertical chemical variability.

Claassen (1973) reports chemical data from eight wells drawing water from the tuff strata in the north, southeast, and southwest areas of the (NTS). The analyses are in good agreement with the previously reported data.

The chemical composition of 15 ground-water samples from Pahute Mesa were reported by Blankennagel and Weir (1973). As with other waters from the tuff aquifer, the ground water of Pahute Mesa is of a sodium potassium bicarbonate type. Sodium plus potassium ranged from 58 to 99 percent of the total cations, with 8 of the samples having the alkali ions present at more than 90 percent. Bicarbonate is the most abundant anion with bicarbonate plus carbonate making up more than 50 percent of the total anions in 12 of the samples. Water from the western side of the mesa has dissolved solids concentrations ranging from 206 to 336 mg/L, and averaging 280 mg/L. In the eastern part of the mesa, the dissolved solids range from 117 to 248 mg/L, and average 200 mg/L. Blankennagel and Weir (1973) consider that the lesser concentrated water in the east may be due to its nearness to areas of recharge.

Chemical analyses for 12 ground-water samples primarily from the northern area of the NTS are presented by Claassen (1985). Claassen (1985) recognized that some of the samples were atypical of the regional tuffaceous aquifer. These samples "all represent very young, generally perched ground water," thus not having evolved chemically to the extent of the waters representative of the regional aquifer. Specifically, the decrease in calcium relative to sodium is presumed to result from greater quantities of clinoptilolite precipitated from a ground-water composition evolved by reaction with vitric tuff and, therefore represents a trend of increasing maturity of ground water.

Figure 3-12 provides a graphical description of water in the tuffaceous aquifer in the form of a Piper diagram.

Lower carbonate aquifer

Schoff and Moore (1964) recognized two varieties of water in the regional carbonate aquifer: a calcium magnesium bicarbonate type and a mixed type. Winograd and Pearson (1976) determined that the variation in composition corresponded to the distance from recharge area. The authors found that ground water in close proximity to the Spring Mountains recharge area was typical of water moving through an upland carbonate; that is, calcium (45 to 69 mg/L), magnesium (10 to 16 mg/L) and bicarbonate (180 to 290 mg/L) occurred as primary constituents, and sodium, potassium, chloride and sulfate were present in negligible quantities. Water that is primarily calcium magnesium bicarbonate is still found at intermediate points along the flow system; however, concentrations of sodium and sulfate are increased. Finally, near the Ash Meadows discharge area sodium, sulfate, and chloride are present as

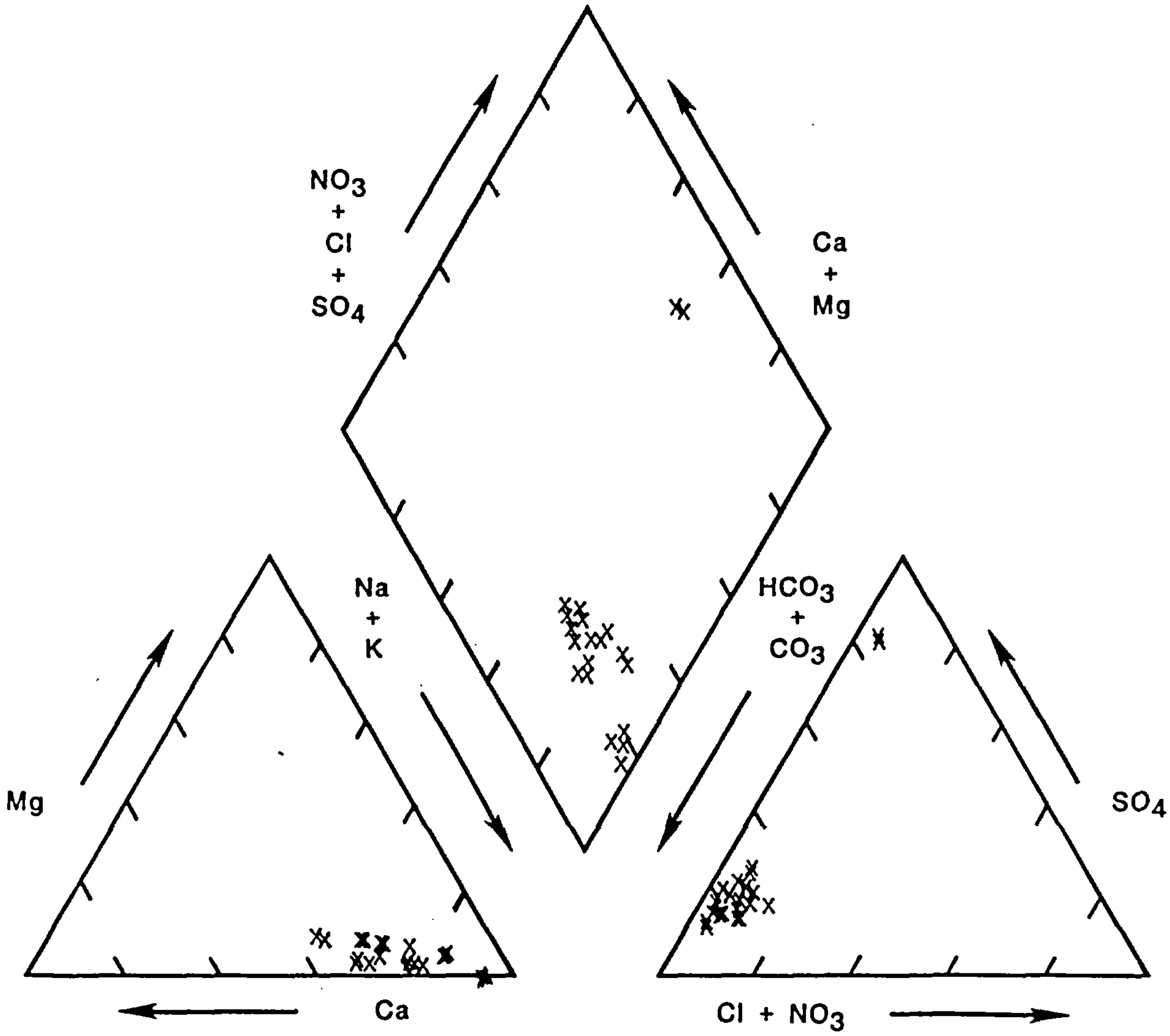


Figure 3-12. Piper diagram showing the regional sodium bicarbonate character of the tuff aquifer.

major ions with concentrations of 69 to 100 mg/L, 80 to 110 mg/L, and 21 to 27 mg/L, respectively. The mixed waters of Schoff and Moore are characterized by these last two types. Winograd and Thordarson (1975) attribute this increase in sodium, sulfate, and chloride to the downward leakage of sodium- and sulfate-rich water from the tuff aquitard. Temperatures are typically between 26 and 38°C, with outliers at 6.5 and 64°C; pH values vary insignificantly around 7.4.

The chemical composition of water from four wells tapping the carbonate aquifer on the eastern side of the NTS are reported in Claassen (1973). Three of the wells are in an area where the carbonate aquifer is directly overlain by tuff beds. As expected, the sodium concentration in these waters is high (up to 142 mg/L) relative to calcium (80 mg/L maximum concentration) and magnesium (33 mg/L). Bicarbonate and sulfate are present in concentrations up to 589 mg/L and 76 mg/L, respectively. The fourth well is in an area where the producing zone is separated from the tuff by 637 ft (190 m) of limestone and dolomite, thereby making sodium less dominant than calcium and magnesium. With the exception of one measurement of 9.9, pH values are between 7.0 and 8.3. Temperatures vary insignificantly around 34°C.

Water quality data for three samples from the lower carbonate aquifer in the southern portion of Ash Meadows ground-water subbasin (Claassen, 1985) are characteristic of the mixed water previously described.

Water from the lower carbonate aquifer is depicted graphically in Figure 3-13 in a Piper diagram.

<u>Valley fill aquifer</u>

Water in the tuffaceous valley fill has a composition similar to that of water in the tuffaceous aquifer shown in Figure 3-12. However, because of the shallowness of the water table in some areas, evapotranspiration results in an increased concentration. Analyses of 16 water samples from the tuffaceous alluvium in Oasis Valley (White, 1979) show sodium concentrations ranging between 100 and 315 mg/L and bicarbonate measuring between 207 and 512 mg/L. Chloride (68-100 mg/L) and sulfate (53-250 mg/L) also show a general increase. Other ions--calcium, magnesium, potassium and fluoride--are present in quantities less than 40 mg/L. Although some additional reaction may occur between the ground water and the tuffaceous detritus, White (1979) maintains that the principal mechanism for concentrating the sodium and bicarbonate is the decrease in volume of water due to the proximity of the water table to the atmosphere and soil zone. Temperatures vary between 18 and 31.5°C.

Claassen (1985) presented analyses for approximately 55 wells and springs tapping the valley fill in the Amargosa Desert. Many of the samples were differentiated as to tuffaceous or carbonate alluvium. All analyses show a wide range of concentrations for sodium (30 to 250 mg/L), calcium (0 to 66 mg/L), bicarbonate (116 to 437 mg/L) and sulfate (25 to 235 mg/L). The average temperature for water in seven wells completed in the valley fill aquifer was reported as 21°C.

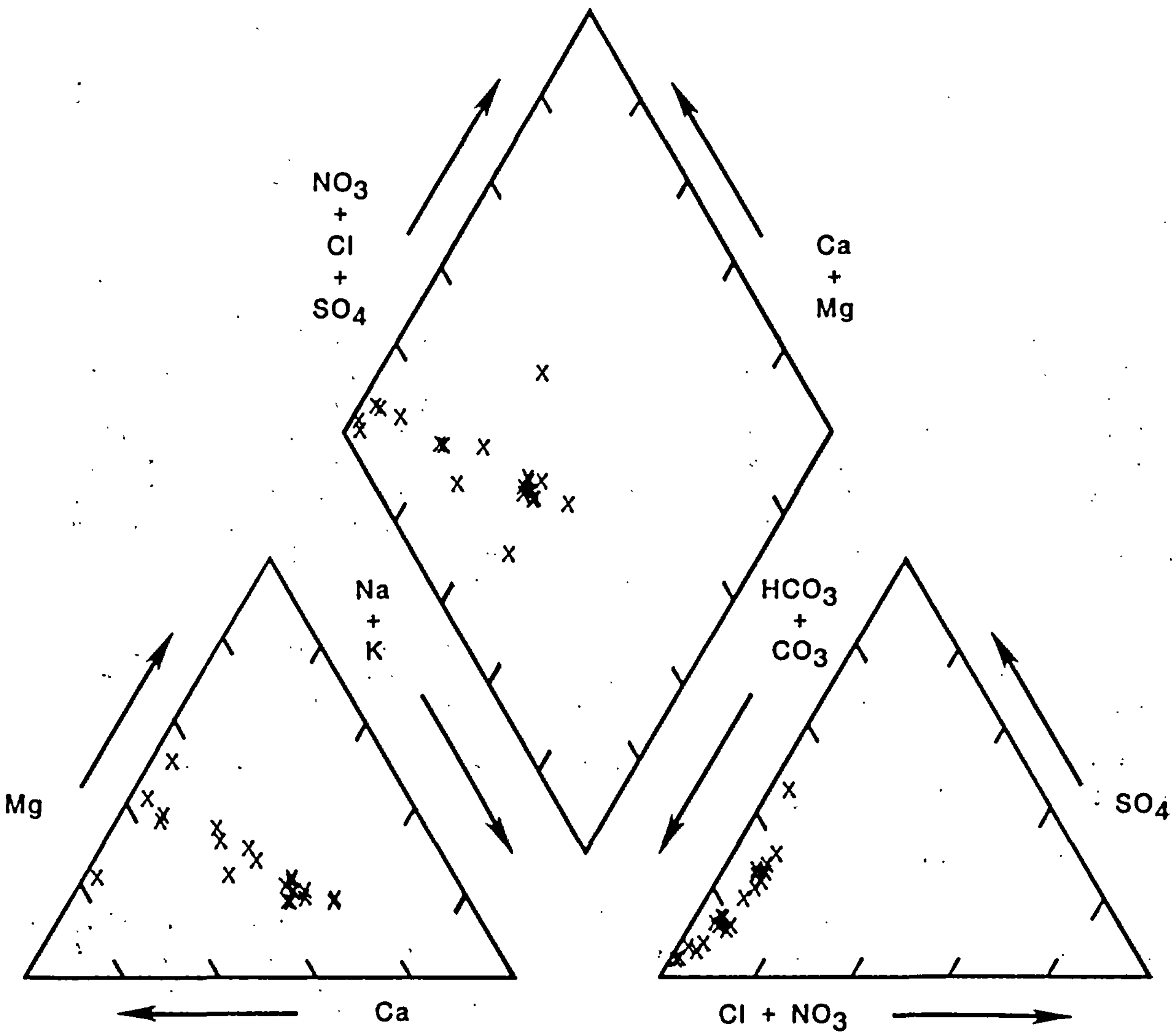


Figure 3-13. Piper diagram showing the regional mixed character of the lower carbonate aquifer.

There are instances where water from each of the above alluvial aquifers shows the effect of local playa deposits. These deposits tend to increase the concentrations of sulfate and chloride in associated ground water. Claassen (1985) reports that six wells in the Amargosa Desert drawing water associated with playas have sulfate and chloride compositions ranging from 89 to 186 mg/L and 24 to 70 mg/L, respectively. By contrast three nearby wells not associated with playa deposits have sulfate and chloride concentrations ranging from 27 to 35 mg/L and 6 to 10 mg/L, respectively.

The chemical composition of water in the valley fill is depicted graphically in Figure 3-14 in a Piper diagram.

3.7.3.1.2 Recharge and discharge mechanisms

Areas and modes of recharge and discharge for the aquifers are discussed in this section, based on the ground-water hydrochemistry.

Recharge to the tuff aquifer

The highlands of Pahute Mesa and Gold Flat serve as probable recharge areas for the tuff aquifer in Oasis Valley. White (1979) shows a linear trend for concentrations of bicarbonate and chloride plotted against sodium for ground water in the tuffaceous aquifers of Oasis Valley, Pahute Mesa and Gold Flat (Figures 3-15 and 3-16). Ground water from the latter two areas plots in the dilute portion of the trend while water from Oasis Valley plots along a more concentrated part of the line. The similarity in composition supports the suggestion of Blankennagel and Weir (1973) that water beneath Pahute Mesa is related to Oasis Valley ground water, and merely represents a less advanced stage in the chemical reaction sequence farther upgradient (White 1979).

Other parts of the tuff aquifer may be recharged differently. Winograd and Thordarson (1975), Claassen and White (1979), and White et al. (1980) discuss recharge at Rainier Mesa. Consideration of altitude and vegetation would include Timber Mountain as a potential recharge area also. One further, and perhaps critically important recharge area, may be Fortymile Canyon. This was first suggested by Winograd and Thordarson (1975); however, Claassen (1985) presents chemical and isotopic evidence to support the hypothesis that major amounts of ground water beneath and in the vicinity of the canyon were recharged by infiltration of surface runoff. This infiltration may have penetrated the tuff aquifer as well as the alluvial aquifers. Plans to evaluate the potential recharge through Fortymile Wash are described in Section 8.3.1.2.1.

Discharge from the tuff aquifer

There are three primary mechanisms for ground-water discharge from the tuffaceous aquifer in the vicinity of the NTS: (1) vertical leakage to the underlying lower carbonate aquifer, (2) subsurface flow infiltrating into the valley-fill aquifer, and (3) spring discharge. Hydrochemical evidence for the first mechanism is presented in the section addressing recharge to the lower carbonate aquifer. The second mechanism is supported by White (1979)

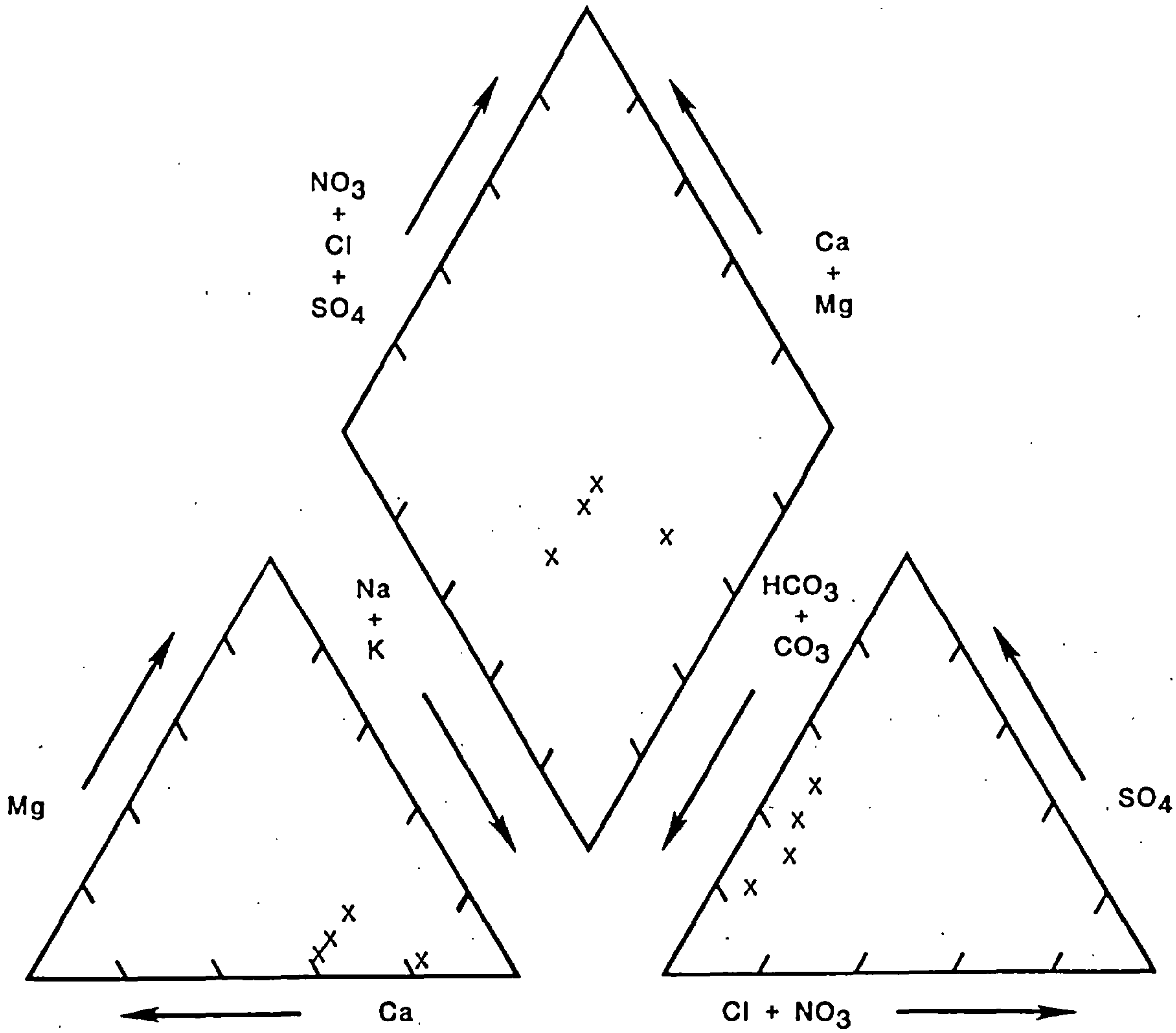


Figure 3-14. Piper diagram showing the regional character of the valley fill aquifer.

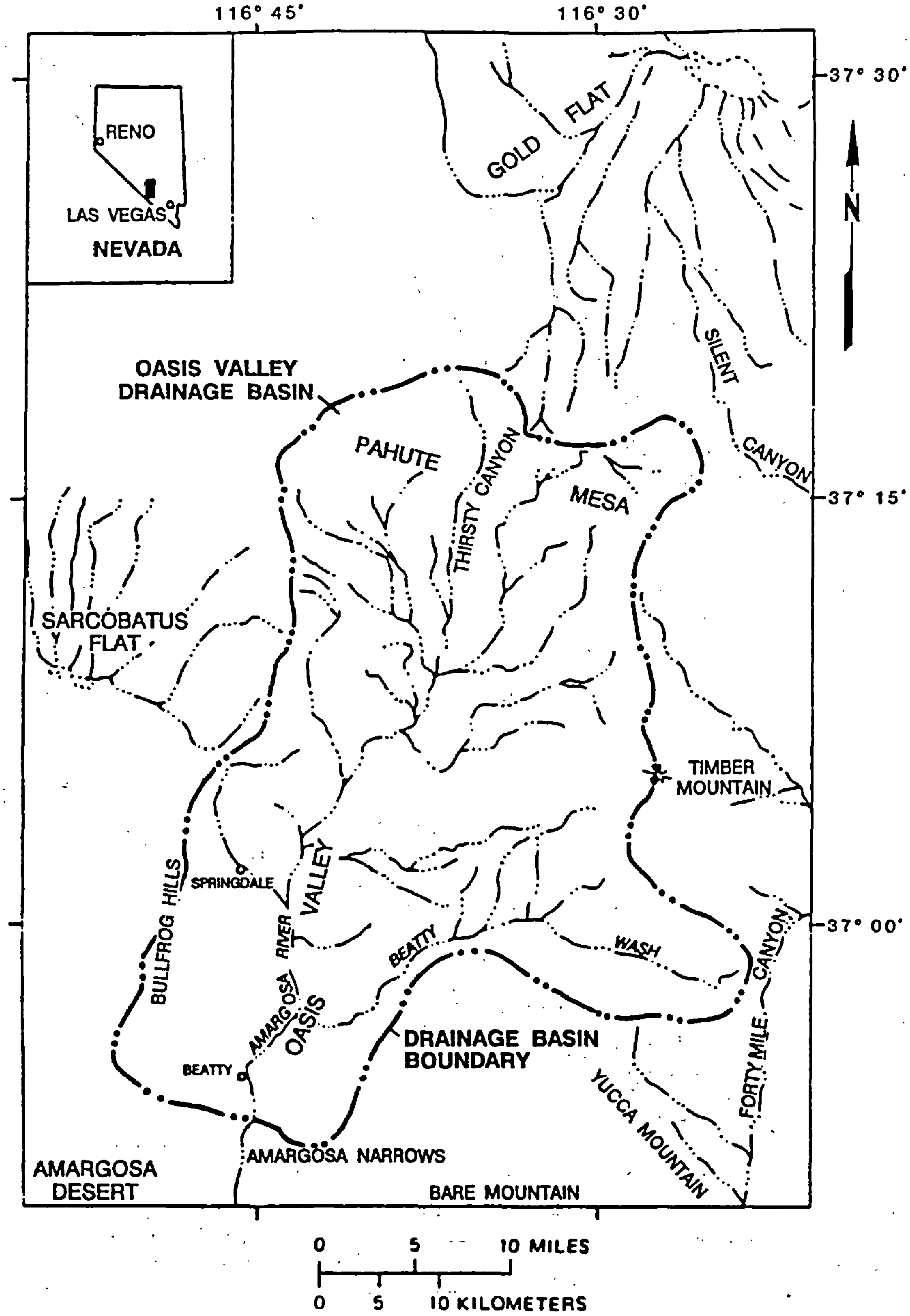


Figure 3-15. General location of Oasis Valley, Pahute Mesa, and Gold Flat ground-water sampling areas. Modified from White (1978).

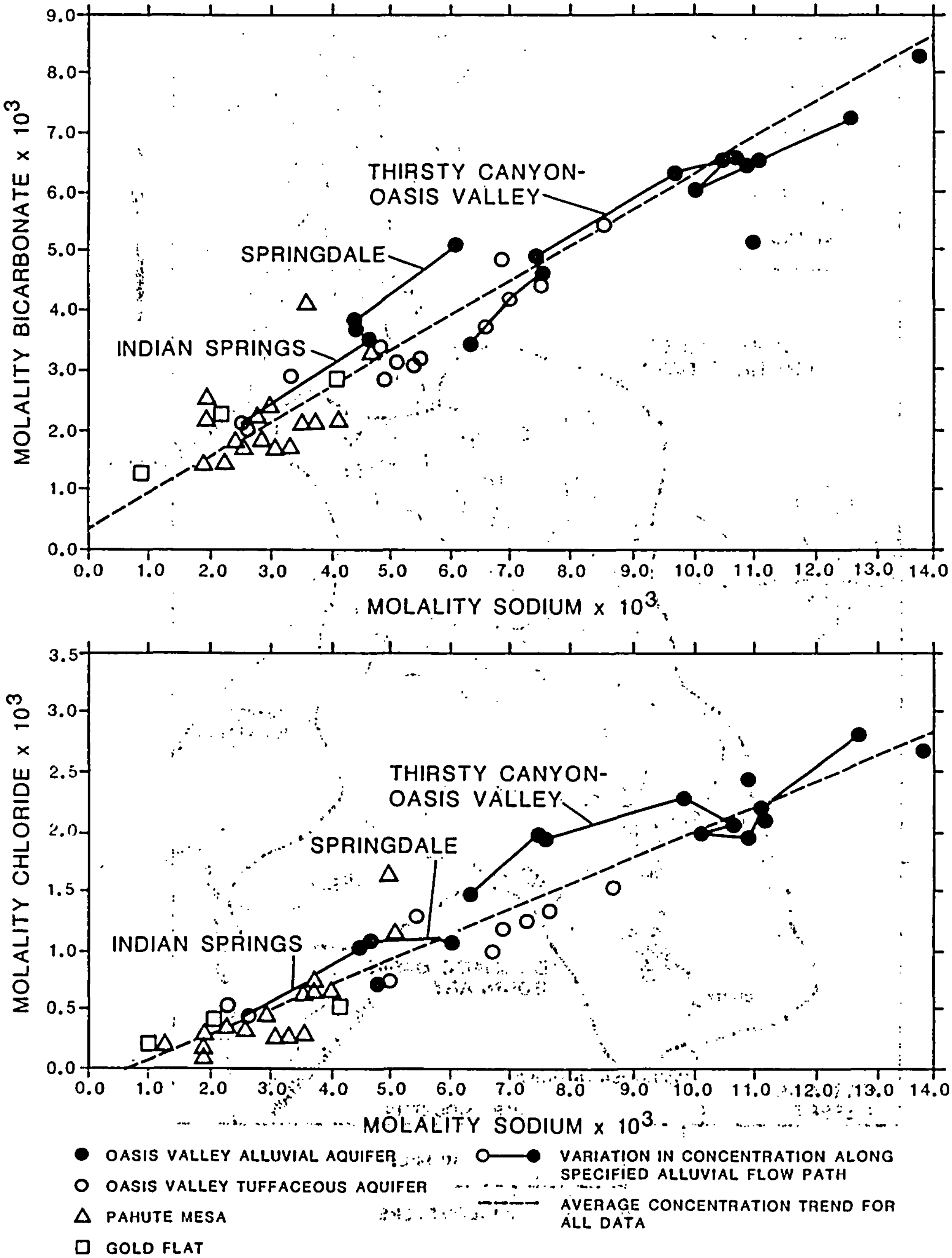


Figure 3-16. Concentration trends of sodium, bicarbonate, and chloride. Modified from White (1979).

where he showed that, through the effects of evapotranspiration, water in the tuffaceous alluvium could be produced from water in the tuff aquifer. White (1979) included data from the Oasis Valley alluvium on his plot of bicarbonate and chloride concentrations relative to sodium (Figure 3-16). Alluvial water compositions for specific flow paths ranged from the dilute region at the initial stages along the flow paths to considerably higher concentrations on the linear trend farther downgradient. White (1979) concluded that based on the linearity of the data, water in the alluvium could evolve from tuffaceous compositions by concentration increases due to evapotranspiration.

The third mechanism, direct spring discharge, is most likely to occur where fracture systems are saturated, broken by recent faulting, or intersect the land surface. White (1979) notes several locations in Oasis Valley where this is evidenced. Although a spring may be issuing directly from the tuff aquifer, Claassen (1985) found that the cation composition of tuffaceous spring water may not necessarily be consistent with that of the regional aquifer. Claassen (1985) explained that the spring discharge is young and generally perched ground water, and thus, has not had the opportunity to evolve to a similar chemical nature as the water from the regional aquifer. Claassen (1985) concludes that although the spring discharge may not be representative of the regional tuffaceous aquifer, it does represent a point in the evolution of the composition of waters in tuffs of southern Nevada.

Recharge to lower carbonate aquifer

The highlands of the Sheep Range, northwestern Spring Mountains, and southern Pahranagat Range are the primary source of recharge to the lower carbonate aquifer. To a lesser extent the Pintwater, Desert, and Spotted ranges also contribute to the recharge (Winograd and Thordarson, 1975). These are highly fractured Paleozoic carbonate rocks that yield ground water of the calcium-magnesium bicarbonate type. However, there are relatively few areas where the lower carbonate aquifer actually yields the calcium-magnesium water characteristic of the recharge areas. This is attributed to vertical leakage in the eastern and northeastern valleys; that is, sodium rich water from the tuff aquifer leaking vertically downward to mix with the calcium-magnesium water in the lower carbonate aquifer. On the basis that Frenchman Flat and Ash Meadows ground waters have nearly identical compositions, Winograd and Thordarson (1975) conclude that vertical leakage of high sodium water must be occurring in northern Indian Springs, northern Three Lakes, and eastern Emigrant and Desert valleys. There are, however, two areas where the carbonate water has had little opportunity to come in contact with tuff or tuffaceous alluvium. Water from these areas, the Spring Mountains and the Pahranagat Valley, show the untainted calcium magnesium chemistry that would result from precipitation in the eastern Paleozoic carbonate highlands.

A second source of recharge to the lower carbonate aquifer is downward leakage of water from the Cenozoic strata. Schoff and Moore (1964) concluded that based on the distribution of sodium, the water in the Paleozoic carbonate rocks underlying the NTS is being recharged by downward percolation through the tuff and tuffaceous alluvium. When added to the calcium magnesium water already in the carbonate rock, the sodium potassium water associated with these tuffaceous rocks yields the water of mixed chemical character, which is generally found downgradient in the Amargosa Desert.

Naff et al. (1974) used a Piper diagram as chemical evidence supporting the idea of downward leakage from the tuff aquifer. Points on the Piper diagram representing downward leakage through the Tertiary aquitard and points representing water moving through a potentiometric trough in the carbonate aquifer just below Yucca and Frenchman flats virtually surround points representing spring water issuing from the carbonate aquifer in the Ash Meadows discharge area (Devils Hole). From this, the authors conclude that the chemical character of the discharge at Ash Meadows can be accounted for by ground water percolating downward across the Tertiary aquitard and mixing with water in the carbonate aquifer. Winograd and Thordarson (1975) used the differences and variations in chemical quality between the carbonate aquifer and the tuff aquitard to estimate that leakage across the aquitard probably constitutes 1 to 5 percent of the discharge at Ash Meadows but may contribute as much as 20 percent.

A third source of recharge to the lower carbonate aquifer, possibly contributing as much as 35 percent (Winograd and Friedman, 1972), is the underflow (i.e., trans-basin regional ground-water movement) into the basin from the northeast. Winograd and Thordarson (1975) found that the chemical data supported the hypothesis that ground water originating in the Pahranagat Valley moves southwestward through the lower carbonate aquifer into the Ash Meadows ground-water basin. Spring water in the Pahranagat Valley was found to have about one-third as much sodium and potassium and about one-half as much sulfate and chloride as that at the NTS downward crossflow from the tuff aquitard in the areas of Amargosa Desert, northern Three Lakes and northern Indian Springs valleys, the calcium magnesium water in the lower carbonate aquifer of Pahranagat Valley could readily be altered to the calcium magnesium sodium type (mixed) found beneath eastern Frenchman Flat.

<u>Discharge from the lower carbonate aquifer</u>

Ash Meadows is the primary discharge area for the lower carbonate aquifer (Section 3.7.2). It is a fault controlled spring line in the south-eastern and east-central part of the Amargosa Desert. Chemical and temperature data clearly show that although the major springs emerge from Quaternary deposits, the water feeding the spring pools is derived by upward leakage from the underlying and flanking lower carbonate aquifer (Winograd and Thordarson, 1975). These authors found that specific conductance measurements of water from 11 major springs emerging from the lake beds at Ash Meadows ranged from 640 to 750 micromho per centimeter at 25°C, with 8 of these springs having measurements not greater than 675 micromho per centimeter at 25°C. The specific conductance for springs issuing directly from the carbonate aquifer (Devils Hole and Point of Rocks) ranged from 645 to 686 micromho per centimeter at 25°C. By contrast, water from wells tapping valley fill had measurements ranging from 300 to more than 1,000 micromho per centimeter at 25°C. Winograd and Thordarson (1975) cite as support for the discharge hypothesis the consistently similar specific conductance measurements between water from the spring pools and water from the lower carbonate aquifer.

Temperature measurements also corroborate the idea that spring discharge is supplied by direct upward leakage from the lower carbonate aquifer. Temperatures for water discharging directly from the lower carbonate aquifer range from 33.5 to 34°C. Water from the lake beds is between 27 and 33°C for yields more than 1,000 gpm (0.06 m3/s), and between 23 and 34.5°C for lower yielding springs. Measurements from deep wells tapping the valley fill indicate that the water in the valley fill aquifer ranges from 19.5 to 28.5°C but is usually less than 24.5°C. No seasonal or long-term variation in water temperature at the major springs is indicated by periodic temperature measurements (Winograd and Thordarson, 1975). As with the specific conductance measurements, the springs issuing directly from the lower carbonate aquifer show similar temperature measurements with those from the lake bed springs.

Areal variations in temperature add further support. Near the carbonate-rock ridges that border the discharge area on the northeast, the buried carbonate aquifer is shallow. Water traveling along a funnel or fault zone to the surface has little time to reach temperature equilibrium with the surrounding cooler Ceonzoic sediments. However, further from the ridges the carbonate aquifer is buried to depths of 1,000 ft (300 m) or more. In this area, the longer travel time of water moving to the surface allows greater loss of heat to the cooler surrounding sediments (Winograd and Thordarson, 1975).

A second mechanism for discharge from the lower carbonate aquifer is direct upward crossflow into the valley fill. Winograd and Thordarson (1975) found that the chemical character of water from two wells tapping valley fill in east central Amargosa Desert was dissimilar to that of water from valley fill wells in other parts of the study area, but resembled quite closely that of water issuing from the springs at Ash Meadows. However, principal ionic concentrations in the valley fill wells (median values) were 10 to 20 percent lower than the median concentrations for the springs at Ash Meadows. The authors suggested that the difference in absolute ionic concentrations was due to the dilution effect of ground water derived from local recharge (having lower dissolved solids content) on water that had leaked up into the valley fill from the lower carbonate aquifer.

Further support for this hypothesis is offered by Claassen (1985). Observations of water quality, temperature, and hydraulic potential indicate that in the eastern part of the Amargosa Desert upward leakage from the lower carbonate aquifer mixes with water that has been recharged directly to the valley fill. Claassen (1985) observes that water quality from four sites associated with playa deposits on the eastern side of the Amargosa Desert does not show the drastic differences with surrounding nonplaya water, as does other playa-affected water in the study area. In addition, the water from these four sites is chemically homogeneous over a large area relative to other playa-associated water. These observations lead Claassen (1985) to the idea that an integrating factor, such as source water leaking up from the carbonates, is in effect.

A temperature of 30.6°C was measured in only one of the aforementioned wells. This temperature is closer to temperatures measured in water from wells in the carbonate aquifer (27 to 30°C) than to temperatures measured in water from wells in the distal valley fills (21°C). Furthermore, at this same location the difference in hydraulic potential between the carbonate aquifer and the valley fill is just 6 m, almost the smallest difference observed in the west central Amargosa Desert. Claassen (1985) explains that the smaller potential difference and the presence of more permeable sand and gravel in the valley fill at this site supports the idea of significant upward leakage from the carbonate aquifer.

Recharge to the valley fill aquifer

There are three principal sources of recharge to the valley fill aquifer: (1) upward leakage from the tuff aquifer, (2) upward leakage from the lower carbonate aquifer, and (3) overland flow. All but the third have been previously discussed under sections relating to discharge from the tuff and lower carbonate aquifers. Surface runoff is considered the most likely recharge mechanism for tuffaceous alluvium in the west-central Amargosa Desert. Winograd and Thordarson (1975) suggested that the low dissolved solids content of water from six wells along Fortymile Wash reflected recharge primarily via infiltration along the arroyo rather than underflow from Pahute Mesa and Timber Mountain. Claassen (1985) found that sodium-calcium-magnesium concentrations of water in the tuffaceous valley fill in the Amargosa Desert were generally inconsistent with the composition of water in the bedrock aquifers to the north. The data showed that the sodium concentration for valley fill ground water was consistently less than that for bedrock aquifers, sometimes as much as 15 percent. Claassen (1985) concluded that valley fill recharge was primarily surface runoff from the tuffaceous highlands infiltrating along present day wash bottoms.

Discharge from the valley fill aquifer

The most likely mechanism for discharge from saturated valley fill is evapotranspiration. Because of the close proximity of the water table to the ground surface in some areas, Oasis Valley for instance, direct exchange with the atmosphere as well as transpiration occurs (White, 1979). White found that along a valley fill flow path, upgradient samples contained less than half the dissolved solids of the water in the alluvium at the lower end of the flow path (458 mg/L compared with 1,040 mg/L). White (1979) acknowledged that there may be some additional reaction between the ground water and tuffaceous alluvium but concluded that the principal reason for the increase in dissolved solids was a decrease in the volume of ground water due to direct evaporation and transpiration through the vegetative cover.

3.7.3.1.3 Hydrochemical facies

The major hydrochemical facies of the NTS and vicinity were delineated by Winograd and Thordarson (1975). These authors recognized the three types of water described by Schoff and Moore (1964) and suggested two additional facies. The hydrochemical nature of the NTS and vicinity can thus be characterized as follows:

1. A sodium-potassium-bicarbonate facies is present in western Emigrant Valley, Yucca Flat, Frenchman Flat, Jackass Flat, Pahute Mesa, and Oasis Valley. Water of this facies is found in tuff, rhyolite, and valley fill aquifers rich in volcanic detritus. Subsequent to the Winograd and Thordarson (1975) studies, Benson and McKinley (1985) provide data indicating that the water of Yucca Mountain is also of this facies.

2. A calcium-magnesium-bicarbonate facies occurs in the Spring Mountains, southern Indian Springs, southern Three Lakes Valley, and Pahranagat Valley. In these areas, wells tapping either the lower carbonate aquifer or the valley fill aquifer rich in carbonate detritus draw water of this facies.

3. The calcium-magnesium-sodium-bicarbonate facies is found in the lower carbonate aquifer between Ash Meadows and the eastern NTS. This facies is the result of mixing the first two facies.

4. The playa facies is recognized to be quite variable, depending to some extent on the depth of the sampling well. Occurrences are restricted to playas where ground water is discharged by evapotranspiration (near Death Valley Junction) or to shallow discharge areas.

5. The sodium-sulfate-bicarbonate facies is found in a few wells in the west-central Amargosa Desert.

3.7.3.1.4 Summary

In summary, the chemistry of ground water in the NTS and vicinity is determined primarily by interactions between water and the reactive components of rock and soil zones through which the water has traveled. Water having moved only through tuff strata or through valley fill rich in tuffaceous detritus has a sodium-bicarbonate nature. Ground water that has traveled only through the lower carbonate aquifer or valley fill rich in carbonate detritus is of calcium-magnesium-bicarbonate character. In areas of downward crossflow from the Cenozoic strata, the lower carbonate aquifer has water of a mixed nature, that is, a calcium-magnesium-sodium-bicarbonate type.

The regional hydrochemical evidence presented contributes significantly to the understanding of the hydrologic system. Recharge to the tuff aquifer in Oasis Valley is principally by underflow and flow from the northern tuffaceous highlands. The lower carbonate aquifer is recharged by precipitation in the Paleozoic carbonate highlands to the northeast. Other sources of recharge to this aquifer are interbasin underflow from the Pahranagat Valley and downward leakage from the Cenozoic strata. In addition to upward leakage from underlying Cenozoic and Paleozoic strata, the valley fill alluvium receives recharge from surface runoff infiltrating along present day stream channels.

Discharge from the tuff aquifer occurs as (1) vertical leakage to the underlying lower carbonate aquifer, (2) subsurface flow infiltrating into the valley fill, and (3) direct spring discharge. Ash Meadows, a fault-controlled spring line, is the primary discharge area for the lower carbonate aquifer. In other areas of the Amargosa Desert, water from the lower carbonate aquifer leaks upward into the valley fill. Evapotranspiration is the most likely mechanism for valley fill discharge.

The data presented are sufficient for a semiquantitative description of the hydrochemical environment of the NTS and vicinity, but additional data are necessary for a fully quantitative understanding. Plans for future hydrochemical studies are described in Section 8.3.1.2.3.2.

3.7.3.2 Regional isotope hydrology

This section discusses the data presently available on regional isotope hydrology for the tuff and the carbonate aquifers.

3.7.3.2.1 Tuff aquifer

The environmental radioisotope content of ground-water samples from the tuff aquifers at Yucca Mountain is discussed in Section 3.9.1.3. Additional data are reported by Waddell (1985) for test wells UE-29a#1 and UE-29a#2 and by Claassen (1985) for the Amargosa Desert and parts of the NTS. These data are also summarized in Section 3.9.1.3.

Radiocarbon dates are available from samples of ground water from the tuffaceous aquifer upgradient from Yucca Mountain. The samples are from wells UE-29a#1 and UE-29a#2, in the bottom of Fortymile Canyon. The major ion composition of the water is very similar to that at Yucca Mountain but it has three-fold the radiocarbon content (Table 3-11). In these two wells the radiocarbon content of water ranges from 75.3 percent modern carbon (pmc) units in the shallower abandoned well UE-29a#1 (which was completed to 65.5 m) to 60.0 pmc in the 86.7 to 213.4-m interval of adjacent well UE29a#2 (Waddell, 1985). This stratification is consistent with occasional rapid wash bottom recharge from ephemeral flow (rain storm water) in Fortymile Canyon. Depth to water here is about 25 m and the upper layers of the section are composed of permeable alluvium and brecciated rhyolite. This recharge hypothesis is confirmed by the high tritium content of the shallower water (62 TU), which could only be derived from precipitation bearing bomb-test tritium recharging the aquifer since the mid-1960s. Since the carbon-14 activity is below 100 pmc, appreciable dilution of these recent recharge waters must have occurred, indicating that the recharging water must have had an even higher tritium concentration. Further indirect support of this mechanism is given by the δ deuterium-δ oxygen-18 (δD-$\delta^{18}O$) data. These data plot on the meteoric-water line significantly above the cold, high altitude recharge waters observed under Yucca Mountain (Section 3.9.1.3). The water shows no sign of evaporitic enrichment and is consistent in isotopic composition with warmer, mid-continental intense rainstorm runoff that could cause Fortymile Wash to flow. Rare, high intensity rainfall events therefore probably currently recharge the shallow tuff aquifer at this location. Note that locations for the Amargosa Valley wells listed in Table 3-11 are shown in Figure 3-17.

Claassen (1985) shows that this tendency for the higher carbon-14 content waters in the tuff to occur along washes also prevails down hydraulic gradient from Yucca Mountain. Wells J-12, J-13, Amargosa-9, and Amargosa-18 are good examples. The recharge through wash bottoms need not be recent, as

Table 3-11. Environmental isotope data for ground-water samples from the samples from the tuff and tuffaceous valley fill aquifers in the region near Yucca Mountain[a]

Well designation[b]	Collection date	δD (o/oo SMOW)[c]	$\delta^{18}O$ (o/oo SMOW)[c]	$\delta^{13}C$ (o/oo PDB)[d]	^{14}C (pmc)[e]	HTO (TU)[f]
UE-29a#1[g]	01/29/82	-92.0	-12.4	-12.6[h]	75.3	62.0
UE-29a#2[g,i]	01/08/82	-93.5	-13.0	-12.6[h]	62.3	11.0
UE-29a#2[g,i]	01/15/82	-93.0	-13.1	-13.1[h]	60.0	11.0
J-12[j]	03/26/71	-97.5	-12.8	-7.9	32.2	<68.0
J-13[j]	03/26/71	-97.5	-13.0	-7.3	29.2	<68.0
UE-25c#1	09/30/83	-102	-13.5	-7.1	15.0	<0.3
UE-25c#2	03/13/84	-100	-13.4	-7.0	16.6	<0.6
UE-25c#3	05/09/84	-103	-13.5	-7.5	15.7	0.6
USW H-6	10/16/82	-106	-13.8	-7.5	16.3	<3.0
USW H-6	06/20/84	-105	-14.0	-7.3	10.0	1.2
USW H-6	07/06/84	-107	-14.0	-7.1	12.4	0.3
USW VH1[j]	02/11/81	-108	-14.2	-8.5	12.2	6.0
AM-4	03/04/74	-103	-13.2	-7.1	19.3	--
AM-9	03/01/74	-102	-12.6	--[k]	28.4	--
AM-11	03/05/74	-101	-13.1	--	20.8	--
AM-13	03/05/74	-102	-13.0	--	19.3	--
AM-15	03/05/74	-104	-13.0	--	18.4	--
AM-18	03/06/74	-102	-13.0	--	27.8	--
AM-20[l]	03/06/74	-102	-12.4	--	13.8	--
AM-21	06/25/74	-99	-13.2	-8.4	27.4	--
AM-23	03/31/71	-103	-13.4	-7.1	17.1	--
AM-25	03/31/71	-102	-13.4	-5.6	15.6	--
NTS#8[m]	03/24/71	-104	-13.0	-12.1	25.4	--

[a]Sources: Data from Benson and McKinley (1985) and as noted in footnotes. AM-samples from Claassen (1985).
[b]Well locations for UE-, J- and USW-holes are shown in Figure 3-22. Well locations for AM (Amargosa) wells are shown in Figure 3-16.

[c]δ deuterium and δ oxygen-18 are reported in parts per thousand relative to the standard mean ocean water (SMOW) standard.

[d]δ carbon-13 is reported in parts per thousand relative to the Peedee belemnite (PDB) carbonate standard.

[e]Carbon-14 activity is reported as a percent of the modern carbon (pmc) standard.
[f]HTO = tritium; reported in tritium units (TU).
[g]Waddell (1985).
[h]Value reported as positive in reference.
[i]Also reported by Benson and McKinley (1985).
[j]Also reported by Claassen (1985).
[k]-- indicates no data.
[l]Completion in tuffaceous material unsure.
[m]Claassen (1985).

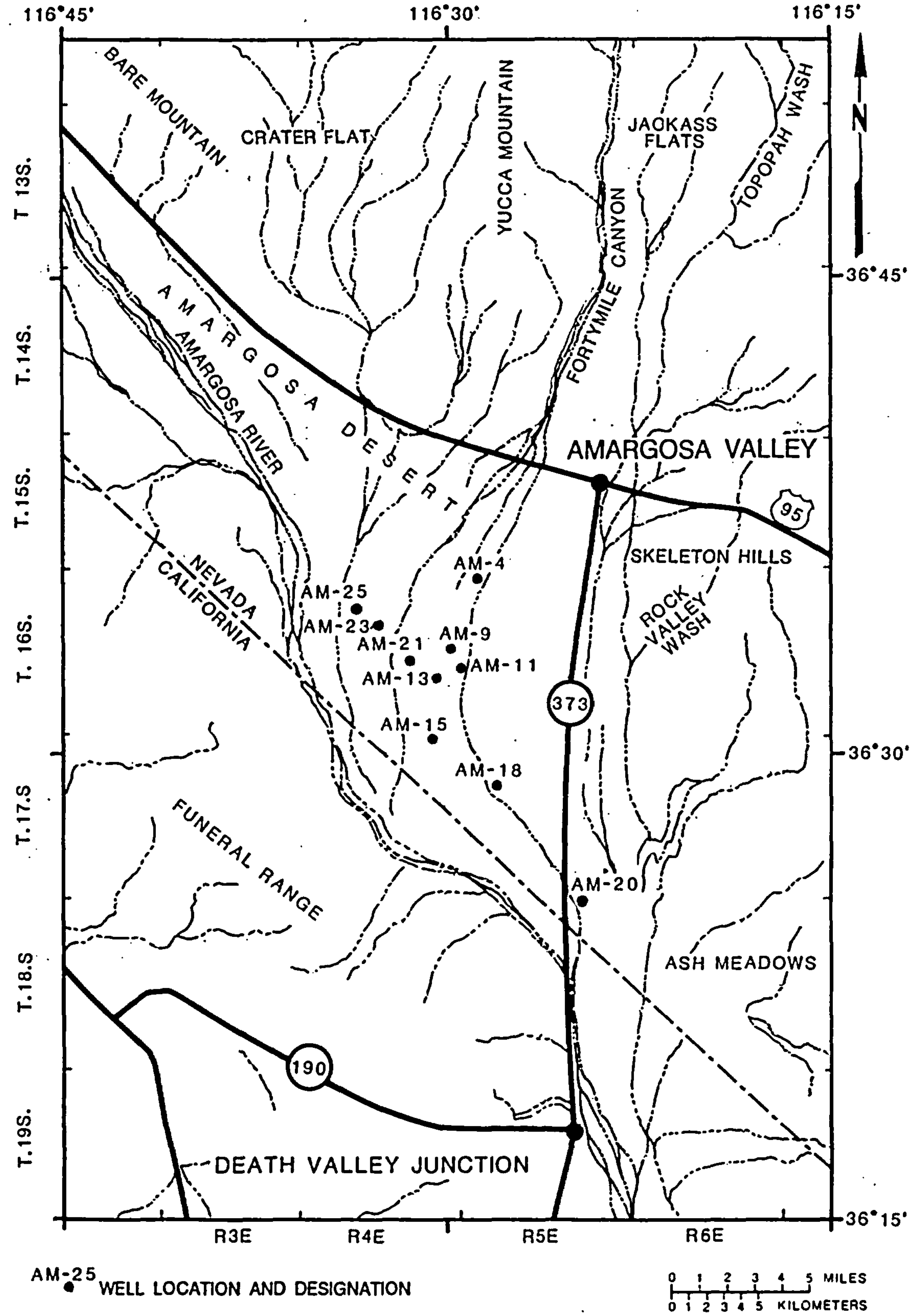


Figure 3-17. Location of Amargosa Valley (AM) ground-water sample wells.

it has been in well UE-29a#2. Claassen (1985) demonstrates that low bicarbonate waters in the tuff having δ carbon-13 ($\delta^{13}C$) values near atmospheric (-7 parts per thousand with respect to the Peedee belemnite carbonate standard (PDB) have probably had minimal isotopic dilution of their original carbon-14 by carbon-12 from carbonate minerals and have not exchanged with biogenic carbon in the soil root zone. Although generally an upper limit, "uncorrected, apparent radio-carbon ages" (i.e., dates obtained by assuming that the initial radiocarbon content of the recharge water was equal to that of the atmosphere (approximately 100 pmc), without correcting for exchange with soil carbon dioxide or carbonate minerals) may be a realistic estimate, in this case, of the true ground-water residence times. In this case, the drainageways also served for paleorecharge. The waters in these locations are no more than 10,000 yr old while the water away from the drainage have apparent ages more on the order of 15,000 yr before present (B.P.).

Figure 3-18 is a δD-$\delta^{18}O$ diagram of the analyses on water samples from the tuff aquifers (in Tables 3-11 and 3-12). The radiocarbon content is plotted (in pmc) at each δD-$\delta^{18}O$ coordinate. The data from Yucca Mountain are circled. The younger, wash-bottom recharge samples fall higher on the plot than does the older, high altitude, cold continental recharge in the same formations under Yucca Mountain (Section 3.9.1.3). This is consistent with rainstorm runoff, rather than snow-melt recharge. The low $\delta^{13}C$ values in both instances suggest that the recharge has always occurred in poorly vegetated areas.

The combined isotopic data is consistent with an arid (poorly vegetated in the recharge zone), continental system recharging through infiltration of surface flow along permeable surface drainages. The recharge water about 15,000 yr ago was typical of cold, high altitude precipitation (or snow melt) and has evolved toward water suggesting warmer rapid recharge from intense storms. This model is consistent with the paleoclimatic interpretation of the area (Sections 3.7.4 and 5.2.1).

Note that even in the most down-gradient (southern) portions of the tuff aquifer system, carbon-14 contents tend not to be less than about 12 pmc (about 17,000 yr B.P. apparent radiocarbon age). Several hypotheses have been advanced concerning the absence of older water (of middle Wisconsin age). Based on ground-water velocity boundary conditions and on paleoclimatic data for the site, Claassen (1985) has proposed that precipitation in the area in the middle Wisconsin may have been inadequate to contribute significant recharge to the tuff aquifer system. Major recharge of the system therefore occurred in the late Pleistocene through the early Holocene. Some minor recharge must still occur today.

The collection of additional ground-water samples, as well as rainfall and snow samples, will contribute significantly to an improved interpretation of this system. Plans for further sample collection are presented in Sections 8.3.1.2.1 and 8.3.1.12.

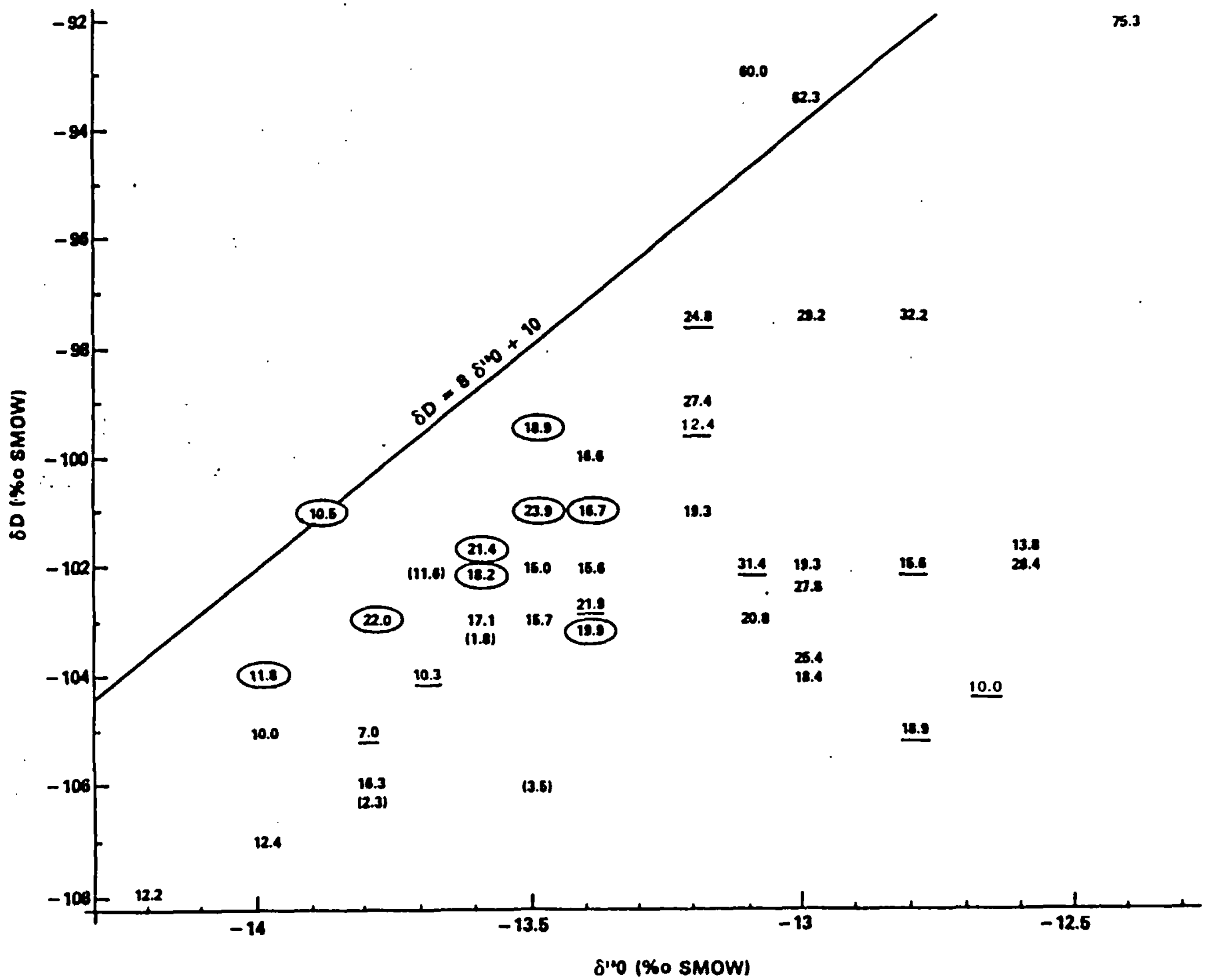


Figure 3-18. $\delta D - \delta^{18}O$ plot of waters from Yucca Mountain area, with radiocarbon content (in percent modern carbon (pmc) units) shown at the corresponding $\delta D - \delta^{18}O$ coordinate. Values in parenthesis are from the lower carbonate aquifer. Underlined values are from mixed carbonate/tuff origin. The remaining values are from the tuff formations, with the Yucca Mountain samples circled.

Table 3-12. Environmental isotope data for ground-water samples from the carbonate aquifer and from mixed carbonate-tuff sources[a]

Well or spring designation	Collection date	δD o/oo SMOW[b]	$\delta^{18}O$ o/oo SMOW[b]	$\delta^{13}C$ o/oo PDB[c]	^{14}C (pmc)[d]	HTO (TU)[e]
			CARBONATE AQUIFER			
UE-25p#1[f,g]	02/09/83	-106	-13.5	-4.2	3.5	<3.1
UE-25p#1[f,h]	05/12/86	-106	-13.8	-2.3	2.3	3.1
16S/51E-23[i]	--[j]	--	-13.6	-4.6	1.8	--
Fairbanks Spring NE[k]	12/13/74	--	--	-5.2	2.2 ± 0.3	0.1 ± 0.2
Fairbanks Spring SW[k]	--	-103	-13.6	-4.9	1.8 ± 0.2	0.0 ± 0.4
Rogers Spring[k]	--	-102	--	-4.6	1.5 ± 0.3	0.0 ± 0.2
Longstreet Spring[k]	--	-103	--	-4.8	2.7 ± 0.4	0.0 ± 0.2
Scruggs Spring[k]	03/10/75[l]	-103	--	-4.7	1.1 ± 0.3	0.2 ± 0.2
Crystal Pool[k,m]	--	-102	-13.7	-5.0	11.6 ± 0.7	0.6 ± 0.4
Devils Hole[k]	--	--	-13.6	-5.0	2.8 ± 0.4	0.3 ± 0.2
King Spring[k,m]	--	-104	--	-4.7	1.7 ± 0.4	0.4 ± 0.2
Big Spring[k,m]	03/09/75	-102	--	-4.6	2.9 ± 0.4	0.3 ± 0.1
			MIXED SYSTEMS			
AM-3[n]	10/20/72	-102	-12.8	--	15.6	--
AM-5[n]	11/17/72	-99.5	-13.2	-6.8	12.4	--
AM-8[n]	03/01/74	-103	-13.4	-7.3	21.9	--
AM-10[n]	06/26/79	-97.5	-13.2	-5.2	24.8	--
AM-16[n]	03/01/74	-104	-12.7	--	10.0	--
AM-17[n]	03/01/74	-105	-12.8	--	18.9	--
AM-19[n]	03/06/74	--	--	--	40.3	--
AM-27[o]	08/18/62	-105	-13.8	-3.6	7.0	--
AM-29[p]	03/31/71	-105	-13.8	-3.4	--	--
AM-30[o]	06/24/79	-104	-13.7	-4.4	10.3	--
AM-47[o]	03/31/71	-102	-13.1	-6.2	31.4	--
AM-50[o]	06/25/79	-104	-13.6	-5.7	--	--
AM-60[p]	12/16/68	--	--	-5.9	28.8	--

[a]Data from Claassen (1985) unless otherwise indicated.

[b]δD and δ oxygen-18 ($\delta^{18}O$) are reported in parts per thousand relative to Standard Mean Ocean Water (SMOW) standard.

[c]Carbon-13 ($\delta^{13}C$) is reported in parts per thousand relative to the Peedee belemnite (PDB) carbonate standard.

[d]Carbon-14 (^{14}C) activity is reported as a percent of the modern carbon standard (pmc).
[e]HTO = tritium; T is reported in tritium units (TU).
[f]Benson and McKinley (1985).
[g]Sampled from the 381 to 1,197 m interval.
[h]Sampled from 1,297 to 1,805 m interval.
[i]Claassen (1985) reports this well as "Amargosa Tracer Well #2."
[j]Data from multiple collection dates.
[k]Winograd and Pearson (1976).
[l]Representative of multiple samplings.
[m]Similar values reported by Riggs (1984).
[n]Tuffaceous lithology, possible carbonate influence.
[o]Carbonate lithology, possible tuff influence.
[p]In both tuff and carbonate formations.

3.7.3.2.2 Carbonate aquifer

Environmental isotope data for ground-water samples from the carbonate aquifer and from mixed carbonate-tuff sources are listed in Table 3-12. Benson and McKinley (1985) have reported isotopic data for ground waters from the carbonate aquifer in the area around Yucca Mountain (drillhole UE-25p#1). Claassen (1985) reports two carbonate aquifer analyses and several analyses on mixed carbonate-tuff systems from the Amargosa Desert. Winograd and Pearson (1976) and Riggs (1984) report analyses of spring water from Ash Meadows, which drains primarily the area to the east of Yucca Mountain and the Amargosa Desert.

All samples from the carbonate aquifer show low carbon-14 contents (<4 pmc; except for Crystal Pool, which is discussed in the following paragraphs), as would be expected at the distal end of a regional carbonate aquifer system. The use of "apparent, uncorrected radiocarbon ages," which may be justified in the tuff aquifer is unsupportable in the carbonate system. The modeling of the carbon-14 content of the recharge waters is extremely complicated in a semiconfined carbonate aquifer system. The carbon-13 analyses show that interaction has occurred between the relatively carbon-14-free carbonate minerals of the aquifer and the flowing ground water. Small adjustments of the isotopic balance to account for this dilution process can greatly affect the resulting radiocarbon dates in such systems (Muller and Mayo, 1986). Without further modeling, these waters can only be taken to be "old," with 30,000 yr B.P. as the conservative upper limit. A very simple example can show why this is an upper limit. A pure carbonate water, one which derived half its carbon from active CO_2 gas and half from dead carbonate minerals, is one half-life younger than its apparent age. Thus, a ground water with an apparent age of 30,000 yr B.P. is probably around 24,000 yr old, if no isotopic dilution occurs as a result of precipitation/dissolution (i.e., isotopic exchange with the aquifer matrix).

The carbon-14 content of ground water at the center of a 16-km-long fault-controlled spring line at Ash Meadows is 5 times greater than that in water from other major springs along the lineament. Winograd and Pearson (1976) have examined the radiocarbon anomaly of Crystal Pool. They have shown it to probably be caused by megascale channeling, with water moving to this discharge point at velocities appreciably greater than those to adjacent springs. Such channeling is consistent with the known flow regime of karstic aquifers.

The data from Claassen (1985) for wells penetrating both tuff and carbonate lithologies show a variability in isotopic compositions expected in mixed systems (Table 3-12). Several of these wells are shallow, with waters also probably derived from valley fill sediments. There are insufficient data available to assess the extent and direction of mixing.

Few deuterium and oxygen-18 data are available for the carbonate aquifer (Figure 3-18 and Table 3-12). The waters show no hydrothermal fractionation and do not resemble expected modern precipitation. Additional stable isotopic data from the carbonate aquifer in the vicinity of Yucca Mountain is expected to provide further information on the interconnection of the tuff and carbonate aquifers. Plans for further data collection are presented in Section 8.3.1.2.

3.7.4 PALEOHYDROLOGY

The purpose of paleohydrologic studies is to determine hydrologic conditions during the Quaternary Period that have differed significantly from present conditions. This information will be used to evaluate the likelihood of episodic conditions recurring that may affect the regional ground-water-flow system over the next 100,000 yr. Of specific interest are (1) the maximum altitude of the water table during pluvial periods of the Quaternary Period, (2) the effects of pluvial water-table rises on shortening of ground-water flow paths to discharge areas, and (3) the magnitude of increases in recharge during pluvial periods. With such information, questions such as the following can be addressed: What is the possibility of the repository being flooded by a rising water table during a return of pluvial conditions? How large an infiltration flux might move through the repository in the future?

Evidence for former, higher water tables, changes in length of ground-water flow paths, and the presence and absence of pluvial lakes in the south-central Great Basin are discussed in the following sections. Although the period of major concern is the past 100,000 yr, the discussion will include paleohydrologic information extending into late Pliocene time.

3.7.4.1 Lowering of ground-water levels during the Quaternary Period

There is geologic evidence for former high levels of the water table in the south-central Great Basin (Figure 3-19) during the Quaternary Period. The evidence consists of tufas, spring orifices, calcitic veins, and cylindrical-lined tubes that mark the routes of former ground-water flow to springs; former water levels marked by calcitic cave deposits on the walls of Devils Hole (a fault-controlled collapse feature at Ash Meadows); and widespread marsh deposits (composed of chalk and authigenic clay) precipitated from former ground waters. Most of these features have been described in reports by Winograd and Thordarson (1975), Dudley and Larson (1976), Winograd and Doty (1980), Khoury et al. (1982), Pexton (1984), Winograd et al. (1985), and Hay et al. (1986). The paleohydrologic significance of these deposits is the subject of papers by Winograd and Doty (1980), Pexton (1984), and Winograd and Szabo (1986).

Winograd and Doty (1980) mapped tufa and vein calcite in the Ash Meadows area of the Amargosa Desert, south of Highway 95 and east of Highway 29. They concluded that the potentiometric surface in the lower carbonate aquifer was once apparently as much as 50 m higher than the highest modern water levels in the Ash Meadows discharge area namely that in Devils Hole (altitude 719 m). Uranium disequilibrium dating of several of these calcitic veins (AM-7, AM-10, and DH-1 in Figure 3-19) show that the higher stands of water levels occurred during Pleistocene time, 1,000,000 to 500,000 yr ago (Pexton, 1984; Winograd et al., 1985; and Winograd and Szabo, 1986).

Still higher and older ground-water levels are recorded throughout the central Amargosa Desert by widespread marsh deposits of ground-water origin. These deposits are described by Khoury et al. (1982) and Pexton (1984). The marsh deposits have been referred to as lacustrine or playa deposits (Walker

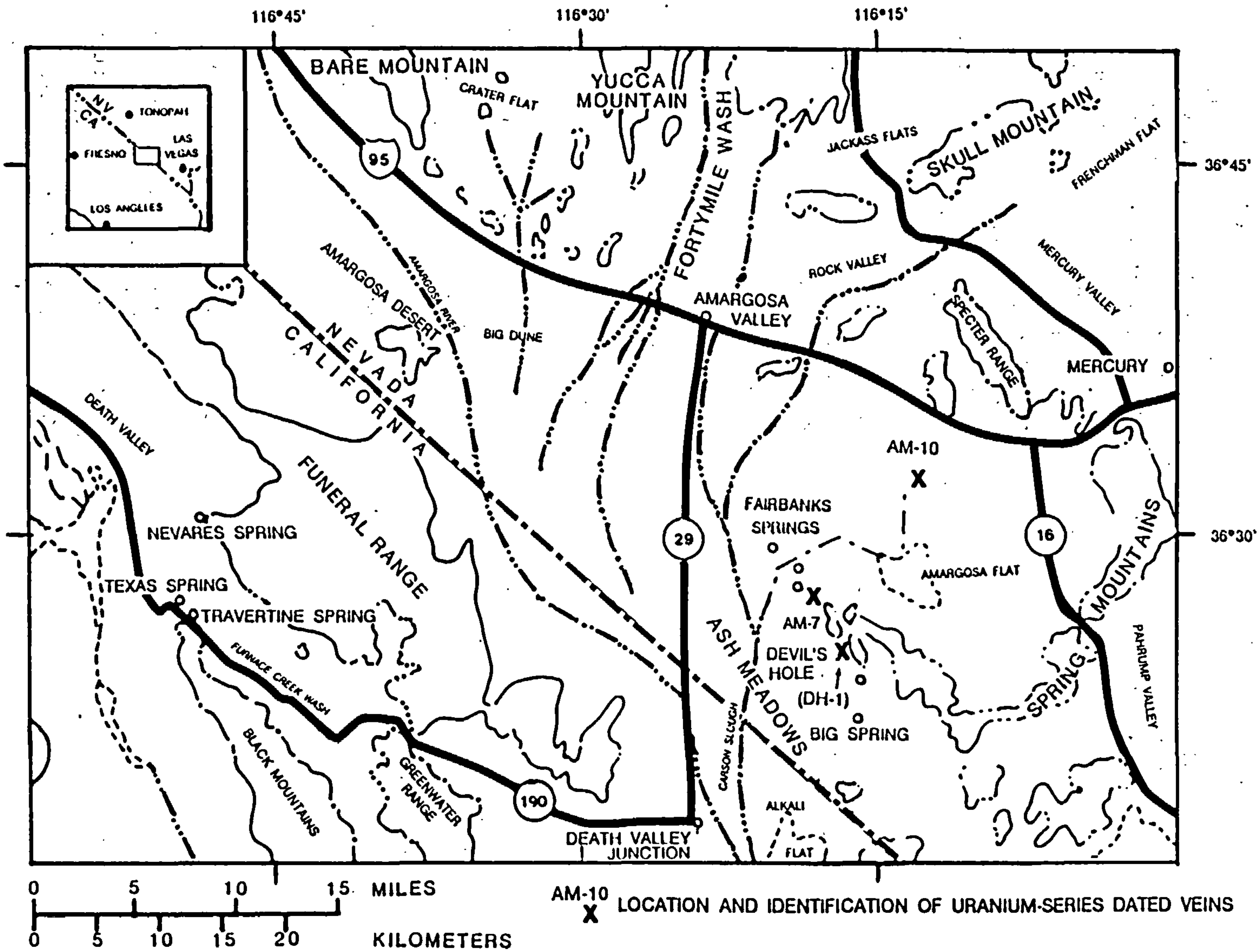


Figure 3-19. Map of South-Central Great Basin showing location of uranium-series dated veins. Modified from Winograd and Szabo (1986).

and Eakin, 1963; Denny and Drewes, 1965; and Swadley, 1983). Hay et al. (1986) present evidence based on stratigraphy, mineral composition, fossil assemblages, and lithofacies relationships that these sediments were deposited in marshes or ponds fed by ground water rather than in lake or playa environments. In this report, they will be referred to as marsh deposits. The marsh deposits occur at altitudes as high as 790 m (Winograd and Doty, 1980) in Amargosa Flat in the east-central portion of the Amargosa Desert. This is about 70 m above the highest modern water level in Devils Hole (altitude 719 m).

A sample from the south end of Crater Flat described as nodular tufa spring deposits has been dated by the uranium-series method to approximately 30,000 yr B.P. (Szabo et al., 1981). Another sample described as seep-deposited tufa or calcrete from the south of Yucca Mountain was dated to 78,000 ± 5,000 yr B.P. (Szabo et al., 1981). These dates may not be correct, however, because this dating method is only considered accurate if the material is from a closed chemical system (Swadley et al., 1984; Bradley, 1985). Szabo et al. (1981) state that these types of deposits may form open systems. Studies to reexamine and redate the deposits are planned and discussed in Section 8.3.1.2. In the Ash Meadows area, these marsh deposits range in age from about 2 to 3 million years (Pexton, 1984) and presumably mark the altitude of regional ground-water discharge during late Pliocene and perhaps earliest Pleistocene time.

The occurrence of the various deposits, marking Quaternary water tables, at altitudes tens to over 100 m above the modern water table probably resulted from a combination of tectonism, water-table lowering due to increasing aridity since Pliocene time, and erosion. Winograd and Szabo (1986) believe that the altitude of the water-table-related deposits at Furnace Creek Wash (Figure 3-19) principally reflect uplift of the terrane, rather than an actual lowering of the water table. However, they infer that regionally the water table in the lower carbonate aquifer is likely to have lowered during the Quaternary Period. The following evidence is cited in support of their hypothesis:

1. The several-thousand-meter topographic relief in Death Valley dates largely from Pliocene and Pleistocene time (Hunt and Mabey, 1966; USGS, 1984), and the movement of the floor of Death Valley probably has been downward relative to sea level and to bordering areas (Hunt and Mabey, 1966).

2. Interbasin flow of ground water through Paleozoic carbonate rock and Tertiary welded-tuff aquifers toward Ash Meadows and Death Valley occurs today (Winograd and Thordarson, 1975). Interbasin flow of ground water toward Death Valley likely also occurred during the Quaternary Period in response to the lowering of ground-water discharge outlets; as a result, Death Valley gradually evolved during the Quaternary into a regional sump for ground water.

3. An increase in aridity due to uplift of the Sierra Nevada and Transverse Ranges would have resulted in a reduction of ground-water recharge.

Another climate-related control on the decline of the regional water table may have been the level of Lake Manly, a Pleistocene lake that filled

Death Valley to about 120 m above sea level (Hunt and Mabey, 1966). With the drying of the lake, ground-water base level in Death Valley would have declined. The exact age of Lake Manly and its duration are not well known. Hunt and Mabey (1966) considered the lake to be no older than the Wisconsin. Hale (1985) suggests that it is much older, perhaps of early- to mid-Pleistocene age. That the lake is either very old, had a short duration, or both, is suggested by the paucity of geomorphic and sedimentologic evidence for its existence (Hunt and Mabey, 1966).

Winograd and Szabo (1986) also suggest that the regional water-table decline postulated for the lower carbonate aquifer during the Quaternary Period was accompanied by a water-level decline in the overlying Cenozoic welded-tuff and valley-fill aquifers. They note that "The suggested progressive lowering of the regional water table throughout the Quaternary does not preclude superimposed and relatively rapid cyclical fluctuations in water level in response to the glacial (i.e., pluvial) and interglacial climates of the Pleistocene." Such fluctuations are discussed in Section 3.7.4.3.

Evidence for increased aridity in the south-central Great Basin is discussed here (also in Sections 5.2.1 to 5.2.3) because of its importance to the above-cited inference of water-table lowering throughout the Quaternary Period. Huber (1981) demonstrated that the central Sierra Nevada has been rising since early Miocene time (23.7 million years ago) and that the rate of uplift has been increasing from approximately 0.03 m/1,000 yr during early Miocene to 0.35 m/1,000 yr at present. In the past 3 million years the Sierra Nevada has risen about 1,000 m. Because the major source of cool-season (November to May) precipitation for the Great Basin is the Pacific Ocean, this major uplift is likely to have significantly reduced precipitation in the region. Warm-season precipitation, which is derived largely from the Gulf of California and the Gulf of Mexico, is not considered important because this moisture is unlikely to contribute much to ground-water recharge (Winograd and Riggs, 1984). G.I. Smith et al. (1983) suggest that when the Sierra Nevada was about 1,000 m lower (3 million years ago), about 50 percent more moisture might have moved into the Great Basin. Based on paleobotanical records, Raven and Axelrod (1978) and Axelrod (1979) believe that aridity increased in the Great Basin, Mojave Desert, and Sonoran Desert during the late Tertiary and the Quaternary periods. They attributed this to uplift of the Sierra Nevada, Transverse Ranges, Peninsular Ranges, and the Mexican Plateau. On the basis of sediment depositional environments, Pexton (1984) believes that the Ash Meadows-Amargosa Desert area became more arid during the Quaternary Period. Winograd et al. (1985) describe a major and progressive depletion in the deuterium content of ground-water recharge in the Spring Mountains (Figure 3-19) during the Quaternary Period, and the most likely explanation for this is a decrease in Pacific moisture due to uplift of the Sierra Nevada and Transverse Ranges.

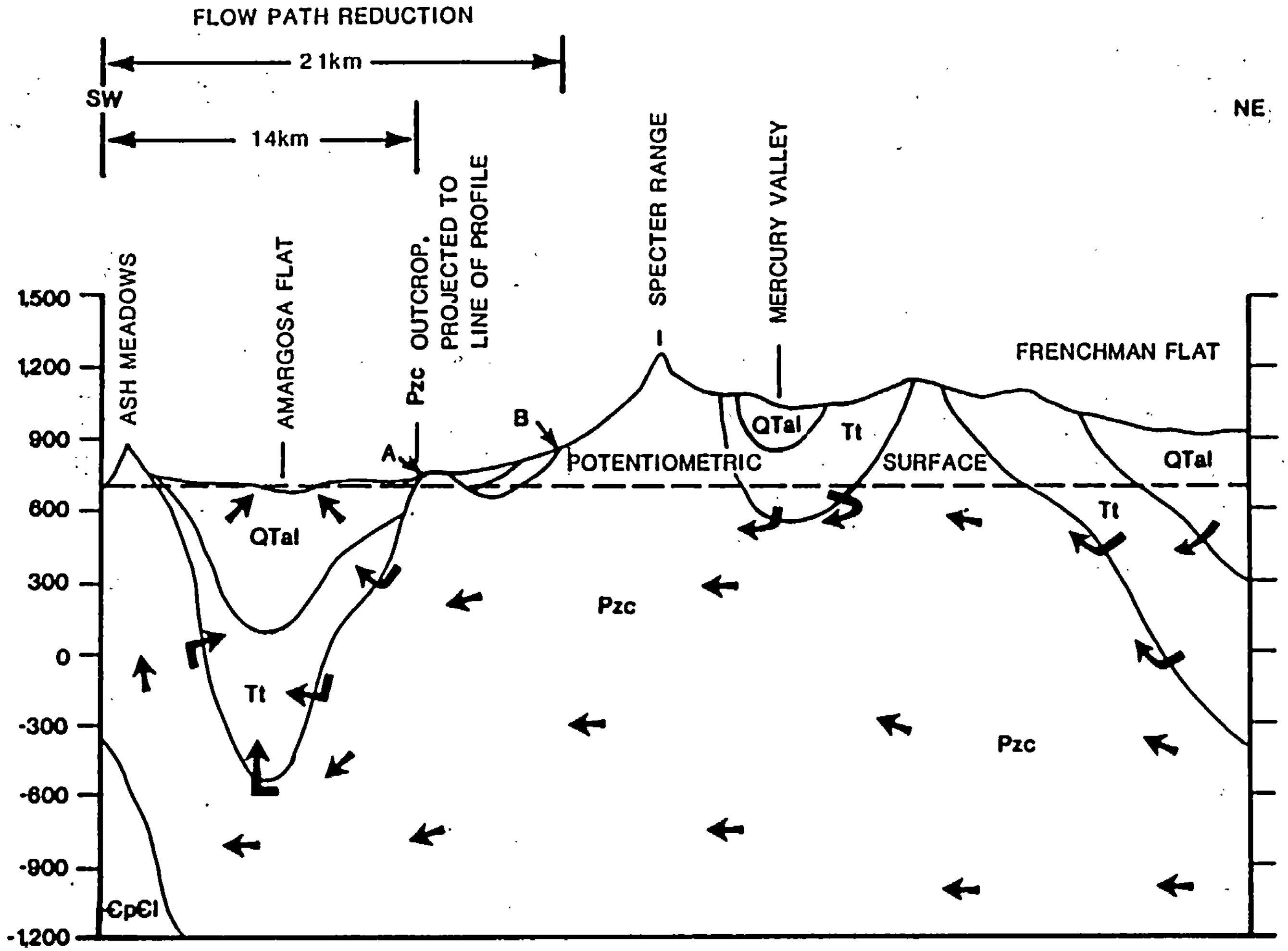
Lowering of the water table at Ash Meadows might have occurred during the Quaternary Period, even in the absence of vertical tectonics or increased aridity. Winograd and Szabo (1986) cite Winograd and Doty (1980), noting that "the major springs at the Ash Meadows oasis (Figure 3-19), differ in altitude by as much as 35 m and are as much as 50 m lower than the water level in Devils Hole. Thus periodic initiation of discharge from new spring orifices (or an increase in existing discharge) in the lower portions of this oasis due to faulting and extensional fracturing would have resulted in new and lower base-levels for ground-water discharge." Implicit in this hypothesis is the belief that the faulting would be extensional opening new (or widening old) avenues of discharge from the buried Paleozoic carbonate rock aquifer that underlies eastern Ash Meadows and that feeds all the modern springs (Winograd and Thordarson, 1975). In support of this hypothesis, Winograd and Szabo (1986) note that most of the calcitic veins in Pliocene and younger rocks at Ash Meadows strike N.40°±10°E. This is nearly at right angles to Carr's (1974) estimate of the direction of active extension in the region, namely N.50°W. to S.50°E. This mechanism may also have periodically lowered the water table in east-central Death Valley where the difference in altitude between the highest (Nevares) and lowest (Texas) major springs discharging from the regional carbonate aquifer is about 170 m (Winograd and Thordarson, 1975).

In summary, available data from calcitic veins and marsh deposits indicate a 50 to 70 m apparent lowering of the water table in the east-central Amargosa Desert since the middle Pleistocene and an apparent lowering of perhaps as much as 130 m since the end of the Pliocene. A strong inference can be made that the water-table altitude in the south-central Great Basin actually declined regionally throughout the Quaternary due to increasing aridity coupled with an absolute lowering of ground-water base level in Death Valley. This postulated general lowering does not preclude superimposed water-table rises in response to pluvial climates of the Pleistocene.

3.7.4.2 Ground-water flow paths during the Quaternary Period

The distribution of calcitic veins, tufas, and marsh deposits also suggest a lengthening of ground-water flow paths during Quaternary time. Regardless of whether the offset in the paleo-water table marked by these deposits was caused by water-level decline or land-surface rise (Section 3.7.4.1), the occurrence of these deposits kilometers to tens of kilometers upgradient from areas of modern ground-water discharge indicates that flow to points of ground-water discharge were shorter in the past. Variations in flow-path length for the Ash Meadows area in response to different water-table levels are shown diagrammatically in Figure 3-20. Ground water formerly discharged from the lower carbonate aquifer about 14 km northeast of Ash Meadows, the present discharge area. Based on the age of a calcite vein (AM-10 in Figure 3-19), this discharge occurred about 750,000 yr ago (Winograd and Szabo, 1986).

The widespread marsh deposits of the Amargosa Desert also show the location as well as the altitude of former ground-water discharge. In east-central Amargosa Desert (east of Highway 29 and south of Highway 95), these deposits were precipitated from ground water discharging from the lower carbonate aquifer, either directly or indirectly via Tertiary aquitards. Like the calcitic veins, they occur as much as 14 km upgradient from Ash Meadows. West of Highway 29 and both north and south of Highway 95 the marsh deposits may reflect not only former discharge from the lower carbonate aquifer (which crops out in the west-central portion of the valley) but also from the Cenozoic welded-tuff and valley-fill aquifers. The marsh deposits in north-central Amargosa Desert are as much as 70 km from Alkali Flat, the modern discharge area in the southern Amargosa Desert.



€p€l LOWER CAMBRIAN AND PRECAMBRIAN CLASTIC ROCKS (LOWER CLASTIC AQUITARD)

Tt TERTIARY TUFF, LAKE BEDS, AND LAVA FLOWS (TUFF AQUITARD)

Pzc PALEOZOIC CARBONATE ROCKS (LOWER CARBONATE AQUIFER)

QTal QUATERNARY AND TERTIARY VALLEY FILL (VALLEY-FILL AQUIFER)

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

DATUM IS MEAN SEA LEVEL
VERTICAL EXAGGERATION: 10.6

Figure 3-20. Diagrammatic section illustrating effects of possible past or future pluvial-related water-table rise on length of ground-water flow path from Frenchman Flat to points of natural discharge at Ash Meadows in the Amargosa Desert. Water-level rises of 40 and 150 m would initiate discharge from lower carbonate aquifer at points A and B, respectively 14 and 21 km northeast of modern spring lineament; arrows depict ground-water flow. Modified from Winograd and Doty (1980).

3.7.4.3 Late Wisconsin lakes, marsh deposits, and ground-water levels

During the late Wisconsin, 21,000 to 10,000 yr ago, average annual precipitation is believed to have been as much as 100 percent greater than modern, with average annual temperature as much as 6°C cooler (Spaulding et al., 1984). Not unexpectedly, changes in climate from late Wisconsin to present conditions have (Section 5.2) produced major changes in the hydrology of the region.

Mifflin and Wheat (1979) discuss pluvial lakes of late Wisconsin age in Nevada. In southern Nevada, they examined Frenchman Flat, Yucca Flat, Gold Flat, Kawich Valley, Sarcobatus Flat, Stonewall Flat, Emigrant (Groom Lake) Valley, Papoose Lake Valley, Pahrump Valley, and Indian Springs Valley, which generally surround the Yucca Mountain area. Of these valleys, they reported shoreline development only in Gold Flat, Kawich Valley, and Emigrant Valley. They report marsh deposits in Indian Springs, Pahrump, and Sarcobatus valleys. Mifflin and Wheat (1979) conclude that "southern Nevada did not contain perennial lakes during the Wisconsinan pluvial," but that "there were likely a number of areas of marsh environments in southern Nevada due to concentrated ground water and spring discharge considerably in excess of present discharge. In south-central and southern Nevada significant differences in the amount and location of ground-water discharge seem apparent."

Hooke (1972) believed that a 90-m deep lake existed in Death Valley about 11,000 yr B.P. Smith and Street-Perrot (1983) agree that there was a lake between 12,000 and 21,000 yr B.P. but conclude that any lake or lakes were small and much shallower.

Quade (1986) reports marsh deposits in southern Indiana Springs Valley. These deposits are assumed to be of late Wisconsin age, based on their stratigraphic and topographic similarity to dated deposits in northwestern Las Vegas Valley. They lie at a maximum altitude of 1,037 m, 20 to 50 m higher than the present water table in the valley-fill aquifer. If these deposits are of ground-water origin, as Quade believes, they may record a higher water table during late Wisconsin time. The marsh deposits occur above an inferred major hydraulic barrier (Winograd and Thordarson, 1975), and are 15 to 20 km downgradient from the Spring Mountains, a major recharge area. These factors may bear on the apparent water-table rise.

Mifflin and Wheat (1979) report marsh deposits, presumably of late Wisconsin age in Sarcobatus Flat and Pahrump Valley. They do not provide information on the location of these deposits so that we cannot compare their maximum altitudes with that of the preirrigation water table in these valleys.

Preliminary uranium-disequilibrium dating of calcitic cave deposits in Devils Hole, in central Ash Meadows suggests a 10-m rise in water level in the lower carbonate aquifer about 30,000 yr ago at Ash Meadows (Winograd and Szabo, 1986).

3.7.4.4 Estimation of future ground-water levels

Winograd and Doty (1980) using a variety of boundary conditions, suggest that during future pluvials, water levels in the regional carbonate aquifer at Ash Meadows and areas upgradient might be a few tens of meters higher than, or perhaps even lower than, modern levels. See Section 3.9.8 for estimation of possible future water levels in the Cenozoic volcanic rocks beneath Yucca Mountain and vicinity.

Winograd and Szabo (1986) concluded that there was a progressive lowering of the water table in the south-central Great Basin during the Quaternary. They noted that "a continued decline of the regional water table in the next 100,000 yr (and beyond?)" was likely (Section 3.9.8).

Craig (1984) makes a comprehensive statistical-climatologic analysis of climate conditions affecting the Death Valley drainage systems that existed during the last glacial maximum. In one analysis, Craig modeled full glacial conditions without assuming a major decrease in lake evaporation rates. In this instance, precipitation increased by 90 percent and pluvial lakes formed in some valleys where lakes are known to have existed in the Late Pleistocene, but no lake formed in Death Valley and the lakes that resulted were not of a size "substantial enough to directly influence the regional groundwater potentiometric surface" (Craig, 1984). In an alternate analysis, Craig (1984) assumes a major reduction in lake evaporation rates. He states that, "If lake evaporation rates decrease by 27 percent, a major lake will form in Death Valley. This lake will be of an extent comparable to the highest recorded stand of Lake Manly during the Wisconsin." Under these climatic conditions, he states "recharge rates, and so ground-water flow conditions, will change significantly during a glacial event". Craig's (1984) basis for considering a 27 percent decrease in rate of evaporation from pluvial lakes was paleoclimatic evidence that evaporation was significantly lower during the Late Pleistocene. As validation for this assumption, he notes that the model predicted "a lake in Death Valley as large as is documented in the geologic record of the late Pleistocene." Craig's (1984) model predicts that such climatic conditions would have sustained lakes in Timber Mountain caldera, in Frenchman Flat, at Ash Meadows, and elsewhere. If Lake Manly and other major lakes existed in Wisconsin time, regional ground-water levels would indeed have been different. However, Lake Manly may be of early-to-middle Pleistocene age (Section 3.7.4.1), when the Sierra Nevada was several hundred meters lower and the Transverse Ranges were not a topographic barrier to inflow of Pacific storms. Thus, the age of Lake Manly has bearing on the validity of Craig's (1984) alternate analysis for reconstruction of late Pleistocene paleoclimatology of the Death Valley area, and by extension for prediction of the effects of future pluvials on ground-water levels. Hunt and Mabey (1966) also note that: "The slight erosion and sedimentation record of Lake Manly may mean that the lake was of brief duration and its level may have fluctuated rapidly. Whatever the cause, this California lake left one of the least distinct and most incomplete records of any Pleistocene lake in the Great Basin." Thus, even if Lake Manly is of Wisconsin age, the climatic changes it portends for the ground-water regime may have been short lived.

The paucity of geomorphic and sedimentologic evidence for Lake Manly makes it difficult to date the age of this major ancient lake in Death

Valley. Resolving whether this lake is closer to 100,000 or 1 million years old would be of value to the paleohydrologic and paleoclimatologic analyses of Czarnecki (1985) and Craig (1984). Application of new or established methods, such as dating of desert varnish (Dorn, 1983) and uranium-series disequilibrium dating of lake-water cemented gravels, may hold some promise (Section 8.3.1.2.1). The reconnaissance (air photo) observations of Mifflin and Wheat (1979), regarding the absence of shorelines of late Pleistocene age in Yucca and Frenchman Flats and the presence of such shorelines in Gold Flat, Kawich Valley, and Emigrant Valley will be confirmed by more detailed study (Section 8.3.1.2.1).

3.7.4.5 Ground-water recharge during late Wisconsin time: carbon-14 evidence

Apparent ground-water ages determined from carbon-14 data (Benson and McKinley, 1985; Claassen, 1985) indicate that much of the ground water within the tuffaceous rocks in the vicinity of Yucca Mountain and within the valley fill aquifer beneath the central Amargosa Desert was recharged during late Wisconsin time, about 10,000 to 18,000 yr ago. Holocene-age (less than 10,000 yr) water occurs in Fortymile Canyon at well UE-29a#2 (4,000 yr B.P.) and at well J-12 (9,100 yr B.P.).

According to Claassen (1985), "little or no radiocarbon dilution probably occurred during the evolution of water in tuff or tuffaceous valley fill; therefore, the unadjusted ages are taken as true ages." He concluded that for ground waters that contain as much as 20 percent of carbonate-derived constituents unadjusted ages could be as much as 1,000 yr too old, and that for a higher percentage there could be a serious problem in determining true ages from carbon-14 data. Since expected ground-water flow paths of waters sampled from Cenozoic aquifers in the vicinity of Yucca Mountain involve little or no contact with carbonate rocks, carbon-14 ages probably are near true ages, provided the well sampled did not tap water of more than one age.

Carbon-14 data from well USW H-6 (Benson and McKinley, 1985) show an increase in apparent ground-water age with depth in tuffaceous rocks. The interval 526 to 1,220 m (the entire saturated thickness penetrated) yielded water with an age of 14,600 yr; the interval 608 to 646 m yielded water 16,800 yr old; and the interval 753 to 853 m yielded water 18,500 yr old. A flow-meter survey (Benson et al., 1983) shows significant water yield between the water table (526 m) and a depth of 790 m. Because water pumped from the entire saturated zone (526 to 1,220 m) included older water from the two deeper zones, it is probable that water in the uppermost part of the saturated zone is considerably younger than 14,600 yr.

Ground water with apparent age dates of 10,000 to 17,000 yr B.P. occurs in the valley-fill aquifer of the central Amargosa Desert (Claassen, 1985), 25- to 40-km downgradient from Yucca Mountain. Claassen (1985) believes, as did Winograd and Thordarson (1975), that ground water in the valley fill represents pluvial recharge resulting from infiltration of surface-water runoff along the distributaries of Fortymile Wash. Therefore, ground waters of about the same age as those beneath the upper zone of saturation near Yucca Mountain could have been emplaced 25 to 40 km downgradient. Plans to evaluate recharge along Fortymile Wash are discussed in Section 8.3.1.2.1.

Section 8.3.1 also discusses plans to evaluate the apparent ground-water ages presented by Benson and McKinley (1985).

Most of the wells sampled by Claassen (1985) that tap tuffaceous valley fill yielded water with apparent age less than 15,000 yr. Speculating on the absence of older water in the central Amargosa Desert, he considered that any water older than 17,000 yr B.P. might have moved downgradient, beyond his study area. Claassen (1985) favors an explanation based on climatic studies, concluding that "snowfall earlier than about 20,000 years B.P. was insufficient to result in snowmelt recharge, while subsequent climatic conditions caused such recharge."

Deducing ground-water velocities from the carbon-14 data is difficult. Claassen (1985) estimates a maximum velocity of 7 m/yr for the region between the head of Fortymile Canyon and the central Amargosa Desert. Claassen (1985) believes that actual velocities are probably much slower, but "because recharge may occur anywhere but not necessarily everywhere along surface drainageways, no probable minimum velocity can be calculated." Because recharge probably occurred by widespread infiltration along distributaries that resulted in layering of waters of differing ages, the estimation of ground-water velocities within the aquifer would be difficult even if test holes were available to selectively sample for carbon-14 ages of water with depth. Plans to drill test holes are discussed in Section 8.3.1.2.3. If recharge of the same-age water can occur simultaneously along long reaches of Fortymile Wash and its distributaries in the Amargosa Desert, map distances may be irrelevant for calculating ground-water velocity. However, under such recharge conditions, it might be possible to draw conclusions regarding paleo versus modern recharge rates and the effects of ground-water velocity on the flushing out of old recharge water (Section 8.3.1.2.3).

3.7.4.6 Conclusions

In summary, the following conclusions can be drawn:

1. Evidence from dated calcitic veins and marsh deposits indicates that the regional water table (more correctly the potentiometric surface) in the south-central Great Basin has apparently declined 50 to perhaps 130 m during the Quaternary Period and that this decline has been accompanied by a lengthening of ground-water flow paths to points of discharge by 14 to perhaps 60 to 70 km. Considerations of the neotectonics of Death Valley, regional interbasin flow through the lower carbonate aquifer, and of the probable increasing aridity in the region during the Quaternary, collectively suggest that an actual and progressive water-table decline occurred in the region during this period.

2. Superimposed on the indicated long-term decline of water table are rises reflecting pluvial climates. In Devils Hole, at Ash Meadows, preliminary uranium-series dating of calcitic cave deposits indicates that about 30,000 yr ago the water table in the lower carbonate aquifer stood about 10 m above modern level. In southern Indian Springs Valley, marsh deposits, of presumed ground-water

origin, occur as much as 20 to 50 m above the modern water table in the valley-fill aquifer; these deposits probably are late(?) Wisconsin in age.

3. Reconnaissance observations indicate that pluvial lakes of late Pleistocene age were not present in Yucca Flat or Frenchman Flat, though such lakes apparently existed in Gold Flat, Kawich Valley, and Emigrant Valley, 70 km north and northeast of Yucca Mountain.

4. Ground water of late Wisconsin age is present in the uppermost part of saturated volcanic rocks beneath Yucca Mountain and in the valley fill aquifer in the Amargosa Desert. The valley fill aquifer was recharged by surface-water runoff along the distributaries of Fortymile Wash. A quantitative interpretation of the carbon-14 data to measure ground-water velocity will require test wells that permit water to be sampled selectively from several depths in the zone of saturation (Section 8.3.1.2.3).

3.8 GROUND-WATER USES

This section identifies the principal regional ground-water users in the hydrogeologic study area (refer to the introduction of this chapter for a discussion of the study area boundaries). The data presented include the locations of areas of heavy withdrawal, the estimated rates of these withdrawals, and the respective hydrogeologic unit sources. The discussion of water use is presented according to the basin divisions given in the introduction and is then further broken down into the hydrographic areas that have been established by the Nevada State Engineer. Water withdrawals within each hydrographic area are summarized according to use when known (irrigation, industrial, commercial, municipal and quasimunicipal, domestic stock-watering); domestic water use is estimated based upon current population data and the guidelines presented in Morros (1982a). Preliminary estimates of repository-related water withdrawals are presented and the potential impacts on local water users are identified. Possible stresses to the ground-water system that could result from repository-related water withdrawals are assessed in light of the current knowledge of the hydrogeologic study area.

The remainder of this section addresses the regional and local ground-water management plans that have been enacted or are proposed within the hydrogeologic study area. The relationship of these plans to repository-related activities and plans for compliance with these State and local restrictions is briefly outlined. Plans for regional monitoring of potential ground-water-related problems are presented in Sections 8.3.1.2 and 8.3.1.16.

3.8.1 REGIONAL AQUIFERS USED FOR HUMAN ACTIVITIES

The regional aquifers in the hydrogeologic study area that are used for human activities are the valley fill aquifer and the lower carbonate aquifer. The welded tuff aquifer is locally important; it is developed only in the southwestern areas of the NTS in support of the former Nevada Research and

Development Area (Figures 3-21 and 3-22). The characteristics of these aquifers and their relationships to each other are presented in Sections 3.6 and 3.7, respectively.

For discussing water use in the hydrogeologic study area, the hydrographic regions delineated by the Nevada State Engineer are the most useful and practical units for consideration (Figure 3-23). For each of the hydrographic areas, the Nevada State Engineer has determined or estimated the perennial yield of the reservoir. The maximum amount of ground water that can be appropriated from a given basin in Nevada is limited to its perennial yield. Thus, the relationship between the perennial yield and the amount of water being used forms the basis for ground-water management in Nevada. When these amounts are known, a quantitative statement of ground-water availability within a specified basin can be made.

Perennial yield (also referred to as safe yield; Todd, 1980) is defined as the amount of water than can be withdrawn on an annual basis from a ground-water basin without depleting the reservoir (Scott et al., 1971). When the amount of withdrawals from a basin exceeds the perennial yield, an overdraft is created that can produce undesirable effects (Todd, 1980) since the water must come from storage within the aquifer. The result is known as aquifer mining and is prohibited in Nevada (Morros, 1982a). When aquifer mining (or over appropriation) is identified within a basin, the State Engineer may issue a statement known as a designation order. The designation order is a means of protecting the aquifer(s) from overuse by defining the boundaries of the area of overdraft and restricting the issuance of permits within that area. Since it is difficult to determine the perennial yield of a basin in which no pumping has occurred (Todd, 1980), aquifer overdrafts tend to be a common problem.

The following subsections discuss current water use for each community located within the three hydrogeologic subbasins of the study area, within the framework of the hydrographic areas. The proposed water use at Yucca Mountain is also examined within this framework, and the potential impacts of repository-related withdrawals are identified. The town of Pahrump, which is located outside of the hydrogeologic study area, is also discussed briefly. The discussion of State and local ground-water management plans and their relationship to activities at Yucca Mountain is deferred to Section 3.8.2.

The town of Pahrump is located approximately 100 km southeast of Yucca Mountain. Studies done by Harrill (1982) and Winograd and Thordarson (1975) indicate that the Pahrump Valley is not located within the boundaries of the Alkali Flat-Furnace Creek Ranch subsystem. Large outcroppings of clastic materials form the mountains to the northwest that separate the Pahrump flow system from the adjacent Ash Meadows subbasin (Harrill, 1982) and allow little or no underflow from the Pahrump Valley into the geohydrologic study area. Well development in Pahrump is completely within the valley fill aquifer, which underlies the community. This aquifer locally receives recharge from the Spring Mountains. Information presented in Harrill (1982) and Winograd and Thordarson (1975) suggests that site characterization activities and the possible subsequent development of a geologic repository in the Alkali Flat-Furnace Creek Ranch basin probably would not affect the Pahrump flow system.

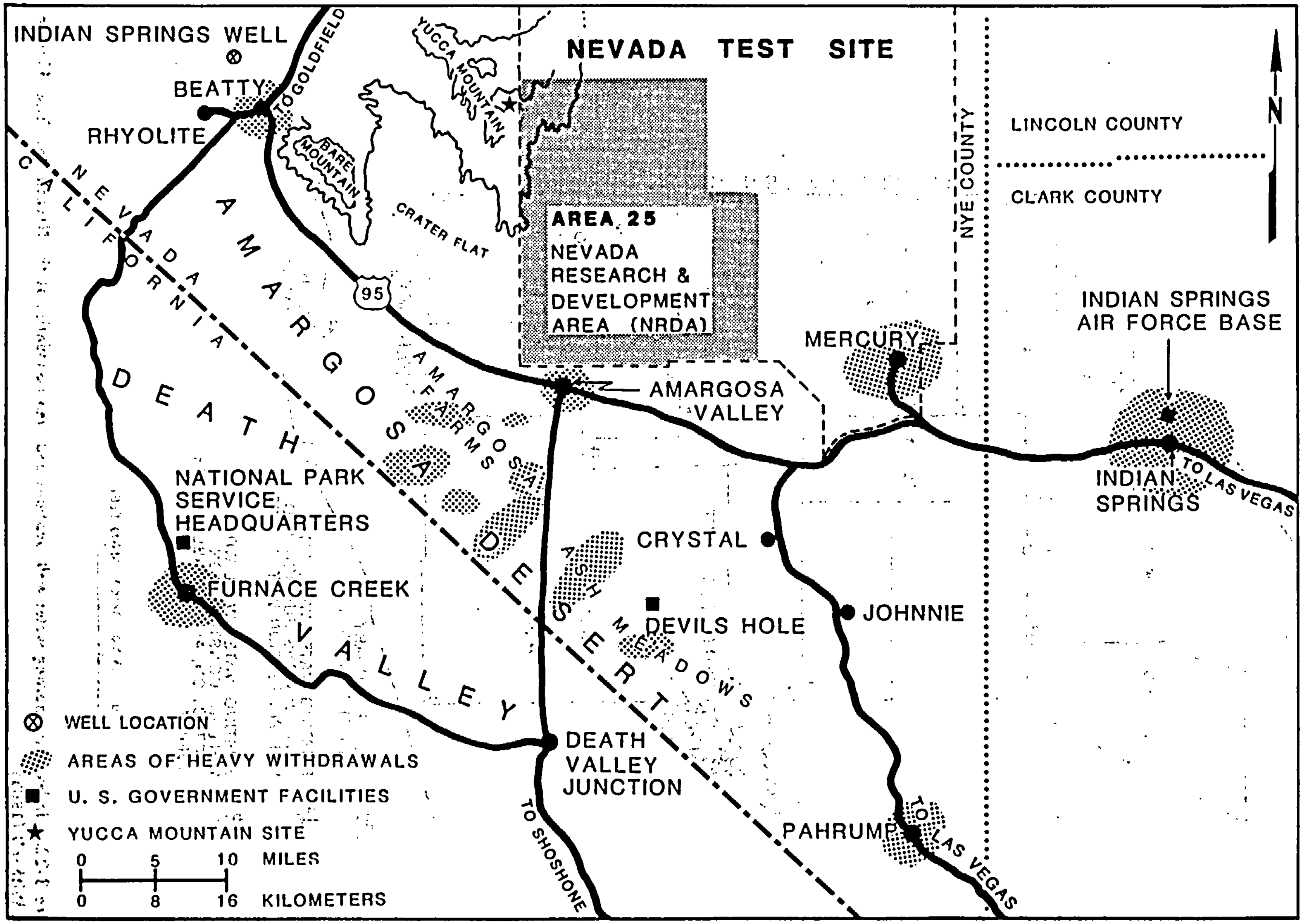


Figure 3-21. Map showing areas of heavy withdrawals near Yucca Mountain. Modified from French et al. (1984).

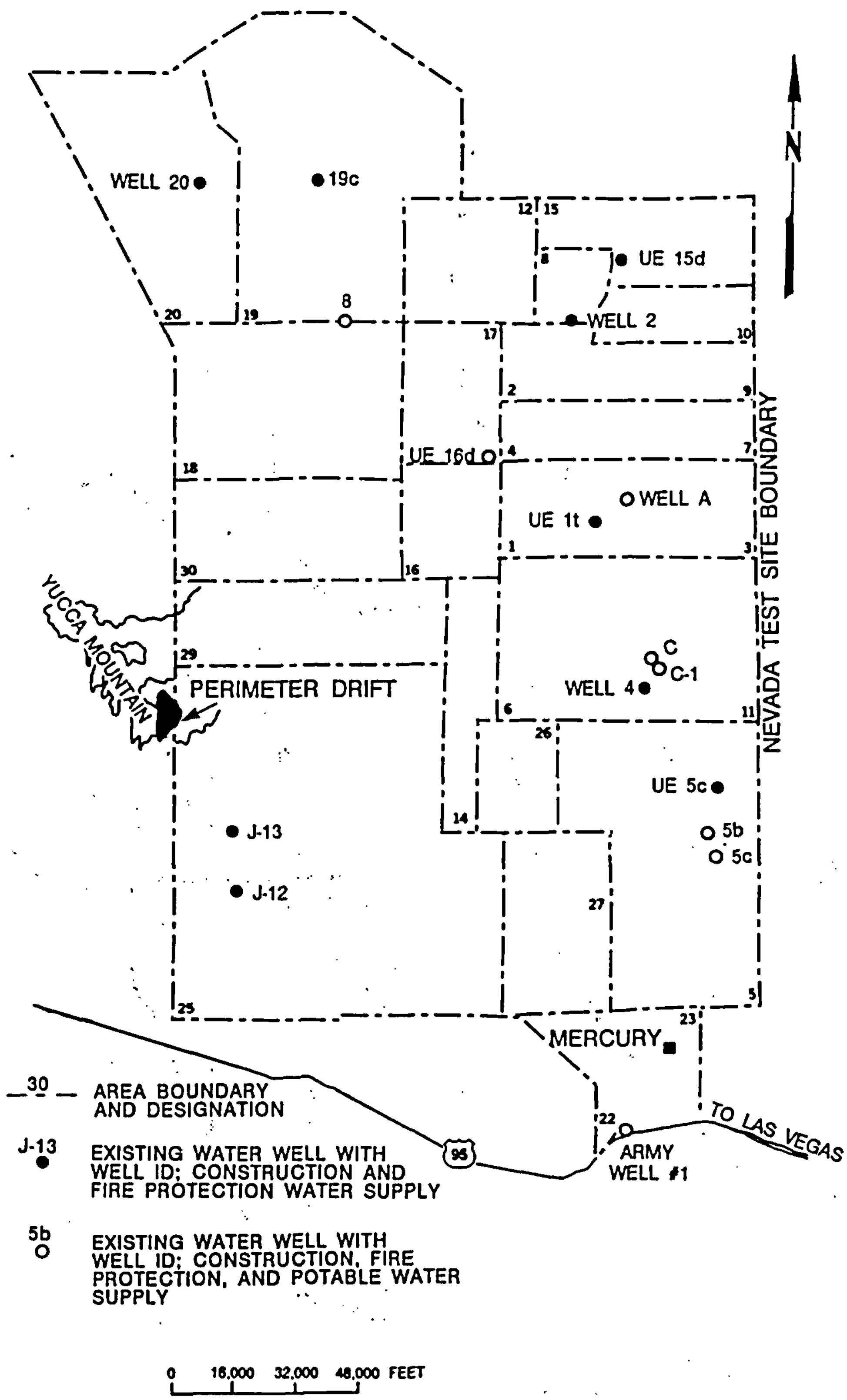


Figure 3-22. Index map showing water well locations and area boundaries at the Nevada Test Site. Modified from Witherill (1986).

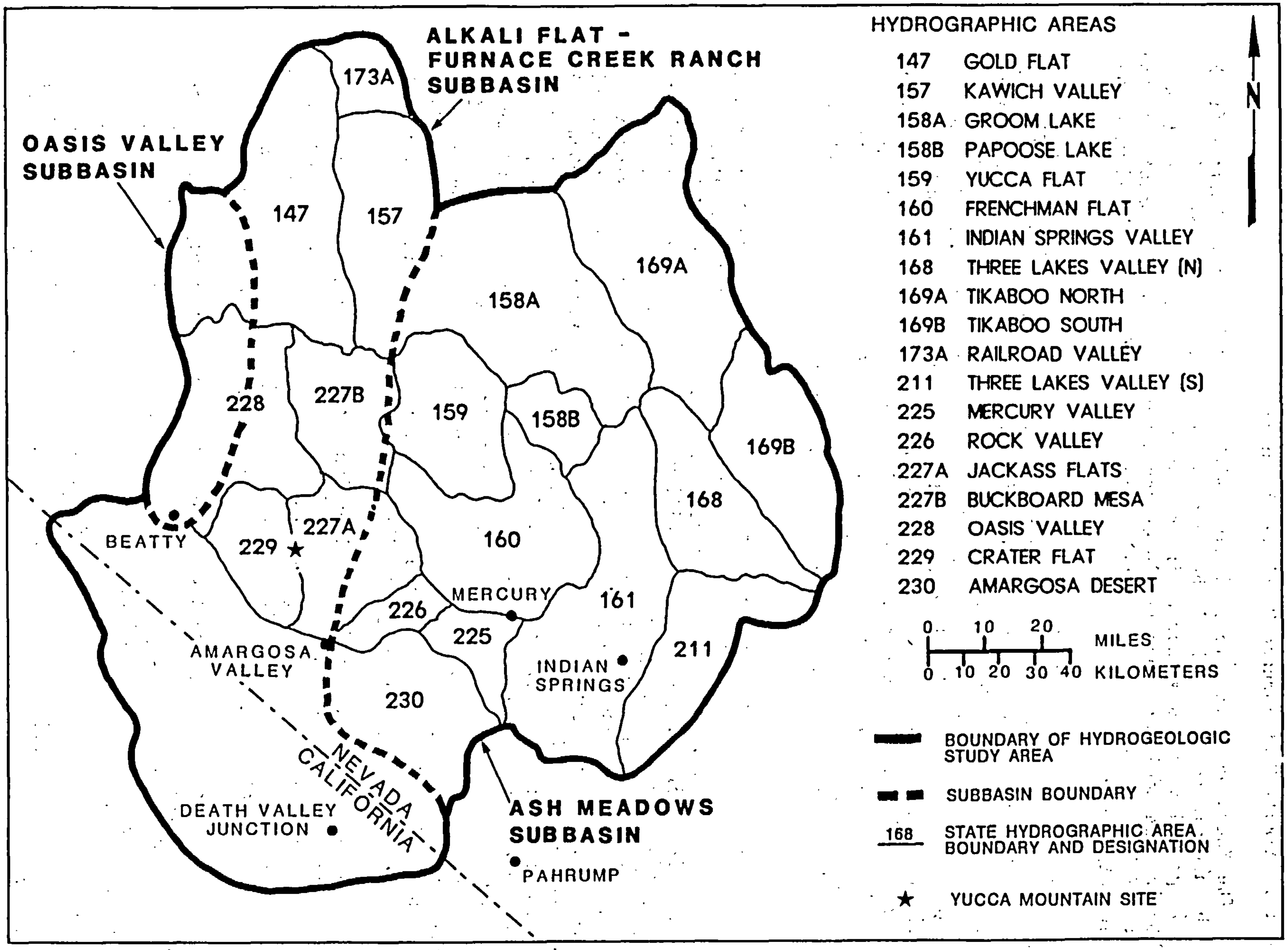


Figure 3-23. Location of Yucca Mountain with respect to the relevant hydrographic areas of Death Valley ground-water system and the hydrogeologic study area. Modified from Scott et al. (1971).

3.8.1.1 Alkali Flat-Furnace Creek Ranch subbasin

The Yucca Mountain site is located within the Alkali Flat-Furnace Creek Ranch subbasin to the north of the Amargosa Desert (Figure 3-23). Very little ground water is withdrawn in the northern and central parts of this subbasin. In addition, very little ground water has been appropriated to the north of Yucca Mountain (upgradient) according to information filed with the Nevada State Engineer's Office.

The major ground-water users in the area, the town of Amargosa Valley and small rural communities of the northeastern Amargosa Desert, are located in the southwestern portion of the Alkali Flat-Furnace Creek Ranch subbasin (Figure 3-23) (French et al., 1984). Most of the water to these users is supplied by wells; however, there has been some spring development. Most residences rely on individual wells, while some trailer parks, public facilities, and commercial establishments are served by small, private water companies. Table 3-13 summarizes the public water suppliers in the area, the type of well used, and the population served. Table 3-14 identifies the total number of known water wells drilled in the Amargosa Desert according to their defined uses. All wells are completed in and produce from the valley-fill aquifer.

The only mineral production operation in the Amargosa Desert is owned by the American Borate Corporation. The operation, located between Amargosa Valley, Nevada, and Death Valley Junction, California (Figure 3-21), was decommissioned in July, 1986. The facility consisted of a large mineral processing plant and a housing development for its employees (French et al., 1984). Water for the community was pumped from a shallow well, having a capacity of 125 gpm (681 m^3/day). The water was treated by a reverse osmosis process before distribution to reduce the total dissolved solids content. A complete analysis of water chemistry is not available, but the fluoride content is known to be greater than State drinking water standards allow. Ground water was also used to supply the mineral processing plant and was obtained from three wells, with reported capacities of 260, 100, and 125 gpm (1,417, 549, and 681 m^3/d). Well log data indicate that all the wells were completed in, and produced from the valley fill aquifer (well logs are filed with the Office of the State Engineer). The plant closed permanently in July of 1986 (<u>Pahrump Valley Times Star</u>, 1986) and water use has ceased.

A small portion of the NTS receives its water from wells drilled in the Alkali Flat-Furnace Creek Ranch basin. Five wells, located in the western areas, supply water for drilling, construction, fire protection, and consumption uses. Table 3-15 summarizes the relevant well data. Section 3.8.1.2 presents information on NTS wells located in the Ash Meadows subbasin.

In addition to well production, a number of springs supply water to the region. The main concentration of springs is in Death Valley in the vicinity of Furnace Creek Ranch, approximately 50 to 60 km southwest of the Yucca Mountain site. Many points of ground-water discharge have been identified in Death Valley National Monument in California (refer to Section 3.5.1 for a tabulation of springs) (Winograd and Thordarson, 1975). The water supply for the National Park Service facilities is derived principally from three groups of springs: Travertine Springs, Texas Springs, and Nevares Springs (French et al., 1984). Discharge data are summarized in Table 3-5. This water is

Table 3-13. Public water suppliers in the community of Amargosa Valley[a,b]

Supplier	Type	Population served
American Borate Trailer Park	Community	300
Amargosa Water Company (IMV)	Community	45
Embrey's Trailer Park	Community	45
Mountain View Apartments and Shopping Center	Community	75
Amargosa Elementary School	Single user	(c)
Amargosa Senior Citizens' Center	Single user	(c)
Coach House Bar	Single user	(c)
Roadside Park 801NY	Single user	(c)
Water-N-Hole	Single user	(c)

[a]Source: SAIC (1986).
[b]Wells are located in the southern portion of the Alkali Flat-Furnace Creek Ranch subbasin and in the southwestern portion of the Ash Meadows subbasin.
[c]In general these systems serve a transient population of at least 25 persons per day.

Table 3-14. Summary of wells drilled in the Amargosa Desert (hydrographic area 230)[a] according to defined use[b]

Type of user	Number of wells
Domestic	199
Commercial	5
Industrial	3
Irrigation	164
Municipal	5
No data	21
Total	397

[a]See Figure 3-23.
[b]Tabulated from well logs filed with the Office of the Nevada State Engineer.

Table 3-15. Nevada Test Site water wells located in the Alkali Flat-Furnace Creek Ranch subbasin[a]

Area number[b]	Well	Pumping rate (gpm)[c]	Unit source[d]	Treatment required	Total withdrawals for 1985, in gal (acre-feet)[e]
18	8	400	Tuff	None	63,683,000 (195.4)
19	19	360	Tuff (?)[f]	None	114,467,200 (351.2)
20	U20a-2	340	Tuff	None	20,165,900 (61.9)
25	J-12	815	Tuff	None	25,049,800 (76.9)
25	J-13	680	Tuff	None	37,811,000 (116.0)

[a]Source: Witherill (1986) unless otherwise noted.
[b]Refer to Figure 3-22 for well locations.
[c]To convert to cubic meters per second, multiply by 6.31×10^{-5}.
[d]Based on information provided in Claassen (1973).
[e]To convert acre-feet to cubic meters, multiply by 1.23×10^{3}.
[f](?) = uncertain. Information regarding specific members is not available.

used both for irrigation and for human consumption. There is no estimate available to indicate the quantity of water required to maintain the National Park Service facilities at their present level of public service (French et al., 1984). The population served by this water supply varies during the year. From October through April, approximately 800 persons live in the area on a semipermanent basis, and an additional 2,000 persons live in the area as visitors. From May through September, the number of semipermanent residents decreases, and there are few visitors (French et al., 1984).

There are three resorts located within the boundaries of the Death Valley National Monument: the Stovepipe Wells Hotel, Furnace Creek Inn, and Furnace Creek Ranch. At Stovepipe Wells Hotel, northwest of Furnace Creek Ranch, potable water was trucked in for many years from a storage tank at Emigrant Ranger Station, 14 km (9 mi) southwest of the hotel. In 1973, the National Park Service constructed an underground storage tank in the alluvial fan south of Stovepipe Wells Hotel and began trucking water to this tank from Nevares Spring. No other improvements to the system have been documented. Pistrang and Kunkel (1964) report that water from an excavated sump lined with buried drainage tile in the Furnace Creek Wash is conveyed in a buried pipeline to the Furnace Creek Inn and Furnace Creek Ranch resorts. The measured flow rate ranged from 190 to 206 gpm (1,037 to 1,123 m^3/d).

Water use within the Alkali Flat-Furnace Creek Ranch subbasin occurs primarily in the Amargosa Desert (hydrographic area 230 in Figure 3-23). The perennial yield to this hydrogeographic area is estimated to be 24,000 acre-feet per year (3.0 x 10^7 m^3/yr) (French et al., 1984). An estimated 17,000 acre-feet per year (2.1 x 10^7 m^3/yr) of this total is naturally discharged from springs and seeps in the Ash Meadows area, and nearly 10,000 acre-feet per year (1.2 x 10^7 m^3/yr) is artificially discharged from wells in the Amargosa Valley. Thus, an overdraft of 3,000 acre-feet per year (3.7 x 10^6 m^3/yr) currently exists. Water levels in wells drilled in the valley fill aquifer declined an average of 12.3 ft (3.7 m) between 1963 and 1984 (Nichols and Akers, 1985). Total appropriations (Table 3-16) in 1985 were over 70,000 acre-feet per year (8.6 x 10^7 m^3/yr); if these rights to appropriate water were exercised, rapid depletion of the valley fill aquifer would result. Given the current and projected population estimates (Smith and Coogan, 1984; DOE, 1986), this scenario is highly unlikely.

Crater Flat (hydrographic area 229 in Figure 3-23) is currently overdrawn because of an appropriation made to Saga Exploration, Inc. for the development of the Panama-Stirling Mine, located on the east side of Bare Mountain (Section 1.7). Although an overdraft exists, no protective measures will be taken (i.e, no designation order will be issued) because the water has been appropriated for mining, which is considered a preferred use under the Nevada Revised Statutes. Under the statutes, overdrafts for mining are allowable for periods not to exceed 5 yr.

Future applications to appropriate ground water in the Amargosa Desert area will be carefully regulated by the Nevada State Engineer; the majority of applications for irrigation permits submitted through 1982 have been denied (Morros, 1982b). Section 3.8.2 discusses the actions that have been taken by the Nevada State Engineer to mitigate overappropriation problems in this area.

In summary, although the Alkali Flat-Furnace Creek Ranch subbasin as a whole is overappropriated, actual annual water use is less than 30 percent of the perennial yield (based on Table 3-16 for 1985). The overappropriation problem exists primarily in the Amargosa Desert (hydrographic area 230 in Figure 3-23). Outside of the Amargosa Desert, a small number of ranches and domestic users withdraw small amounts of ground water. The amount of water withdrawn in hydrographic areas other than the Amargosa Desert represents only a fraction of the perennial yield that is available to those areas (Table 3-16).

3.8.1.2 <u>Ash Meadows subbasin</u>

Several small, unincorporated communities are located within the Ash Meadows subbasin. A large part of the NTS, including the community of Mercury, is also located within this subbasin. Very little water is withdrawn in this subbasin.

Table 3-16. Perennial yields, total appropriations, and actual water use for 1985 in the hydrographic areas making up the Alkali Flat-Furnace Creek Ranch subbasin

Hydrographic area[a] Number	Hydrographic area[a] Name	Perennial yield (AFY)[b]	Total appropriations (AFY)[c]	Water use in 1985 (AF)[d]	Comments
227A (West)	Fortymile Canyon (Jackass Flats)	2,000	320.0	192.9	Yucca Mountain site
227B	Fortymile Canyon (Buckboard Mesa)	3,600	NA[e]	0	Nevada Test Site (NTS)
228 (East)	Oasis Valley	1,000	1.10	ND[f]	
229	Crater Flat	900	2533.48[g]	2533.48	
230	Amargosa Desert	24,000	71,613.66	9,672.0[h]	Overappropriated; designated
147 (East)	Gold Flat	1,900	ND	292.4	NTS
157	Kawich Valley	2,200	ND	0	
173A (South)	Railroad Valley (southern part)	ND	ND	ND	
Subbasin Totals		35,600	74,468.24	12,690.78	

[a]Hydrographic areas are shown on Figure 3-23.
[b]From Scott et al., 1971. AFY = Acre-feet per year. To convert to cubic meters per year, multiply by 1.23×10^3.
[c]Tabulated from preliminary abstracts filed with the Office of the Nevada State Engineer.
[d]Data from Giampaoli, 1986. AF = Acre-feet. To convert to cubic meters, multiply by 1.23×10^3.
[e]NA = not applicable.
[f]ND = no data.
[g]Appropriations for mining and milling may exceed the perennial yield because (1) appropriations for mining activities are for short-term use, and (2) mining and milling applications are considered preferred water uses by the State Engineer.

[h]Data from Coache, ca. 1986.

The Ash Meadows area is located 42 to 60 km (26 to 37.5 mi) southeast of Yucca Mountain (Figure 3-21). Water is pumped from the lower carbonate aquifer (Dudley and Larson, 1976). Virtually all irrigation withdrawals of ground water in this area currently are made by the Preferred Equities Corporation (Giampaoli, 1986). Water from 8 major wells, supplemented by 3 small capacity wells, is used to irrigate more than 12 km^2 (4.6 mi^2) of cropland. Pumping peaked at a rate of approximately 1.2 million cubic meters per month during the years 1970 and 1971. Detailed pumping records were not maintained after 1971, while the land was controlled by the Spring Meadows, Inc. (Dudley and Larson, 1976). In 1971, ground-water withdrawals associated with the planned development of a large agricultural enterprise caused a decline in the water level of the pool at Devils Hole (Dudley and Larson, 1976). This natural pool formed from the collapse of the limestone bedrock, is the only remaining habitat of the endangered species, Devils Hole pupfish, Cyprinodon diabolis.

As a consequence of court action, ground-water withdrawals in this area are now restricted to a degree that is sufficient to maintain the water level in Devils Hole (Dudley and Larson, 1976). The land, which was previously owned by the Preferred Equities Corporation, was turned over to Nature Conservancy in 1986 and then transferred to the Federal Government (Giampaoli, 1986). Other springs in the Ash Meadows area are discussed in Section 3.5.1.

The NTS receives its water from wells operated by Reynolds Electrical and Engineering Company, Incorporated (REECo). The NTS accommodates a worker population of approximately 5,000 individuals, most of whom reside in Las Vegas and other nearby communities; a very small percentage of this workforce resides in Mercury on an intermittent basis.

There are 12 NTS wells that currently withdraw water from the Ash Meadows subbasin for construction, drilling, fire protection, and consumption uses. Some of the water requires treatment before distribution. Table 3-17 summarizes the available information for these 12 wells. Section 3.8.1.1 presents the same type of information for NTS water wells located in the Alkali Flat-Furnace Creek Ranch basin.

The unincorporated community of Indian Springs, Nevada (population 912) is located 80 km (50 mi) east-southeast of Yucca Mountain (Figure 3-21). The community receives its water from the Indian Springs Sewage Company, Inc., which is a public corporation owned by stockholders. As of 1981, there were 53 water customers, including several trailer parks with multiple connections. The company has one well that is completed at the depth of 590 ft (180 m) and is capable of pumping at a rate of 550 gpm (2,998 m^3/d). The water from this well meets State drinking water standards and requires no chemical treatment. The water supply system is metered and is a separate system from that which supplies Indian Springs Air Force Base (French et al., 1984).

Approximately 80 other shallow, domestic wells in the Indian Springs area are in use. Information regarding water quality and quantity for these wells is unavailable. All wells in the area are probably completed in the valley-fill aquifer (Giampaoli, 1986), which is thought to be recharged locally by the lower carbonate aquifer (Winograd and Thordarson, 1975).

Table 3-17. Nevada Test Site water wells located in the Ash Meadows subbasin[a]

Area number[b]	Well[b]	Pumping rate (gpm)[c]	Unit source[d]	Treatment required	Total withdrawals for 1985, in gal (acre-feet)[e]
1	UE1t	270	ND[f]	None	5,594,200 (17.2)
2	2	165	Lower carbonate aquifer(?)[g]	None	20,630,500 (63.3)
3	A	160	Valley fill	Chlorination	39,182,300 (120.2)
5	5b	240	Valley fill	None	6,107,800 (187.5)
5	5c	325	Valley fill	None	61,170,400 (187.7)
5	UE5C	350	ND	None	4,319,000 (13.3)
6	C	270	Lower carbonate aquifer(?)	None	26,162,900 (80.3)
6	C-1	280	Lower carbonate aquifer(?)	None	26,170,300 (80.3)
6	4	650	ND	None	41,815,300 (128.3)
15	UE15d	270	Tuff	Chlorination	ND
16	UE16d	194	ND	None	15,605,000 (47.9)
22	Army Well-1	530	Lower carbonate aquifer(?)	Chlorination	53,916,700 (165.4)

[a]Data from Witherill (1986) unless otherwise noted.
[b]Refer to Figure 3-22 for well locations.
[c]gpm = gallons per minute. To convert to cubic meters per second, multiply by 6.31×10^{-5}.
[d]Based on information provided in Claassen (1973), and Winograd and Thordarson (1975, plate 2b).
[e]To convert gallons to cubic meters, multiply by 3.785×10^{-3}.
[f]ND = No data.
[g](?) = uncertain.

(Refer to Sections 3.6 and 3.7 for discussions of aquifer characteristics and local recharge areas.)

Indian Springs Air Force Base is located adjacent to the community of Indian Springs, Nevada. The population, including military personnel and their dependents, is approximately 900 persons. The water distribution system for this installation is owned and operated by the U.S. Air Force. Three wells, probably completed at shallow depths, supply water to the base. Two of the three wells are used for potable supply; the third well no longer provides potable water due to the presence of organic materials. All water distributed through this metered system is chlorinated to control bacteria (French et al., 1984).

Table 3-18 summarizes known water use in the hydrographic areas of the Ash Meadows subbasin. Very little water is pumped outside of the areas and communities previously discussed. Indian Springs Valley (hydrographic area 161 in Figure 3-23) is currently overappropriated. Actual water use in 1985 exceeded the perennial yield to the basin. Adverse effects resulting from overdraft include a decline in the static water level (SWL) and a reduction in spring discharges (Giampaoli, 1986). Information provided in Table 3-18 suggests that Yucca Flat (hydrographic area 159 in Figure 3-23) is currently overdrafted. Well data in Table 3-17 indicate that these withdrawals may be from the lower carbonate aquifer. On the basis of this information and the fact that there is no detectable decline reported (Witherill, 1986), it is reasonable to conclude that Yucca Flat is not overdrawn. An overdraft also appears to exist for Frenchman Flat (hydrographic area 160 in Figure 3-23). All withdrawals in this area are from the valley-fill aquifer and have been in excess of the perennial yield since 1964 (Claassen, 1973). There has not been any decline in the SWL, which suggests that the estimated perennial yield is too low (Claassen, 1973; Witherill, 1986).

As can be seen from Table 3-18, little of the ground water in the Ash Meadows subbasin is currently privately appropriated or used. Since much of the land within this basin is under the jurisdiction of federal agencies and has been withdrawn from the public domain, future private appropriation of the water is not expected.

3.8.1.3 Oasis Valley subbasin

The Oasis Valley subbasin encompasses the western parts of the Gold Flat and Oasis Valley hydrographic areas, 147 and 228 (Figure 3-23) respectively. Very little ground water is used in this area because of the low population density.

The unincorporated community of Beatty, Nevada (population 925), receives its water from the Beatty Water and Sanitation District. The water is supplied from four wells; three are located in town, and the fourth (Indian Springs Well) is approximately 6.4 km (4 mi) north of the town (Figure 3-21). The system supplies water to approximately 25 customers and the source capacity is about 500,000 gpd ($1.9 \times 10^3 m^3/d$) (Gram, 1985). The water quality of the three wells in town, which produce from the valley fill aquifer (White, 1979), does not meet State drinking water standards because

Table 3-18. Perennial yields, total appropriations and actual water use for 1985 in the hydrographic areas making up the Ash Meadows subbasin (page 1 of 2)

Hydrographic area[a] Number	Hydrographic area[a] Name	Perennial yield (AFY)[b]	Existing appropriations (AFY)[c]	Water use in 1985 (AF)[d]	Comments
158A	Emigrant Valley (Groom Lake)	2,500	59.8	ND[e]	
158B	Emigrant Valley (Papoose Lake)	<10	0	0	
159	Yucca Flat	350	NA[f]	537.5	Nevada Test Site (NTS)
160	Frenchman Flat	100	NA	388.5	NTS
161	Indian Springs Valley	500	754.98	679.0[g]	
168	Three Lakes Valley (N)	4,000	11.48	ND	
169A	Tikaboo North	2,600	21.72	ND	
169B	Tikaboo South	4,000	ND	ND	
211	Three Lakes Valley (S)	5,000	ND	100[g,h]	

Table 3-18. Perennial yields, total appropriations and actual water use for 1985 in the hydrographic areas making up the Ash Meadows subbasin (page 2 of 2)

Hydrographic area[a] Number	Name	Perennial yield (AFY)[b]	Existing appropriations (AFY)[c]	Water use in 1985 (AF)[d]	Comments
225	Mercury Valley	8,000	NA	165.4	NTS
226	Rock Valley	8,000	320.0	ND	
227A (East)	Fortymile Canyon (Jackass Flats)	2,000	NA	0.	NTS
Subbasin totals		37,060	1,117.98	1,870.4	

[a]Hydrographic areas are shown on Figure 3-23.
[b]Data from Scott et al. (1971). AFY = Acre-ft per year. To convert to cubic meters per year, multiply by 1.23×10^3.
[c]Tabulated from preliminary abstracts filed with the Office of the Nevada State Engineer.
[d]AF = Acre-feet.
[e]ND = no data.
[f]NA = not applicable.
[g]Data from Giampaoli (1986).
[h]Estimated use at Indian Springs Correctional Center.

of excessive fluoride (water chemistry data are presented in Section 3.7.3). The EPA recently raised the maximum allowable fluoride content; if the State of Nevada raises its limits, the water from these three wells could meet the new standard with minimal treatment. The fourth well, located north of Beatty at Indian Springs (not to be confused with the community of Indian Springs, Nevada), is of higher quality and does meet the current State drinking water standards. This well is believed to produce from a perched tuff aquifer (White, 1979). Well production capacity from the Indian Springs well has recently decreased from 389 to 86 gpm (2.1×10^3 to 4.7×10^2 m^3/d) due to overpumping and subsequent dewatering of the aquifer (Gram, 1985). Five commercial establishments (Bailey's Hot Springs, Fran's Star Ranch, Ray's Last Stand, Scottie's Junction, and Cottontail) have water supplies and are available to the public. These establishments are all single-users and generally serve transient populations of 25 or fewer people per day. Outlying ranches in the area around Beatty have their own wells.

There are two gold mines operating in the Beatty area that require water for production purposes. The mines are owned by E. R. Fegert, Incorporated, and are located near Rhyolite and the boundary of the Death Valley National Monument. Water for production originates from two sources: One of these is a well owned by the company that produces 40 gpm (218 m^3/d). There are no data available to indicate the aquifer from which the well produces. An additional 483,000 gal (1,828 m^3) of water per month originates from one of the in-town wells operated by Beatty Water and Sanitation District (French et al., 1984). These mines are currently in the developmental phase; when planned future expansion is realized, peak employment will be approximately 100 persons. Another well is planned that will supplement the current water supplies (French et al., 1984).

Table 3-19 summarizes the known water use within the portions of Gold Flat and Oasis Valley basins (hydrographic areas 228 and 147 in Figure 3-23) that are located within the Oasis Valley subbasin. Note that although water use does not currently exceed the perennial yield in either basin, Oasis Valley (hydrographic area 228) has been designated. The designation of this area by the Nevada State Engineer was a protective measure to prevent the overappropriation.

The water-supply problems that the community of Beatty is experiencing are not related to the designation of the basin (Section 3.8.2.2). A solution may now be imminent since the EPA raised the allowable limit of fluoride content in drinking water.

3.8.1.4 Proposed water use at Yucca Mountain

Water-use estimates for site characterization and subsequent repository construction and operation at Yucca Mountain are still in the early stages of development. The water-use figures presented in this section are preliminary and will probably change as more is learned about Yucca Mountain.

Wells J-12 and J-13, located along Fortymile Wash, supply water to the former Nuclear Research and Development Area facilities at the NTS (Young, 1972). Both of these wells are completed in and producing from the welded

Table 3-19. Perennial yields, total appropriations and actual water use for 1985 in the hydrographic areas making up the Oasis Valley subbasin

Hydrographic area[a] Number	Hydrographic area[a] Name	Perennial yield (AFY)[b]	Total appropriations (AFY)[c]	Water use in 1985	Comments
147(Southwest)	Gold Flat	1,900	NA[d]	ND[e]	Nevada Test Site
228(West)	Oasis Valley	2,000	1528.72	Minor[f]	Designated
Subbasin totals		3,900	1528.72	Minor	

[a]Hydrographic areas are shown on Figure 3-23.
[b]Data from Scott et al. (1971). AFY = Acre-feet per year.
[c]Tabulated from preliminary abstracts filed with the Office of the Nevada State Engineer.
[d]NA = Not applicable.
[e]ND = No data.
[f]Data from Giampaoli (1986).

tuff aquifer (refer to Section 3.6.4 for a description of aquifer characteristics). Well J-13 was in continuous service from 1962 to 1969 and caused only a slight decline in the water level (Thordarson, 1983; refer to Section 3.9.7). By 1980, the static water level had recovered to within 0.1 m (0.3 ft) of its original elevation as water withdrawals became intermittent. A more detailed discussion of wells J-12 and J-13 appears in Section 3.9.7.

Test results by Thordarson (1983), Claassen (1973), and Young (1972) indicate that the welded tuff aquifer contains adequate water to supply repository construction, operation, and closure (Morales, 1986). The maximum annual water demand for the repository is anticipated to rise to a peak of 120 million gal (454,200 m^3) per year by the end of the seventh year of construction, and decrease to about 115 million gal (435,280 m^3) per year, and remain at this level for the next 25 yr. The minimum average water demand for the following 23 yr of operation would be approximately 2.5 million gal (9,462 m^3) per year (Morales, 1986). Estimates of the quantity of water needed to support site characterization activities are considerably less. Preliminary estimates from Pedalino (1986) indicate that maximum total water use, for all phases of the exploratory shaft construction and testing will be 41,507,100 gal (1.57×10^5 m^3) (Table 3-20). Section 8.4 provides plans for construction of the exploratory shaft and surface facilities.

To date, published information on water use in the hydrogeologic study area indicates that siting a geologic repository at Yucca Mountain probably would not adversely impact other local users (DOE, 1986). According to current plans (Morales, 1986), water for site characterization activities would be drawn from wells J-12 and J-13 (welded tuff aquifer) until a distribution system could be constructed.

The local effects of ground-water withdrawals vary between the different areas previously discussed. The most recent potentiometric map of the hydrogeologic study area was constructed by Waddell et al. (1984) (Figure 3-9). Contour lines of the potentiometric surface are drawn at 100 m intervals, and are too general to show drawdown from pumping. Figure 3-24 shows the potentiometric surface in the Amargosa Desert, as measured from wells in 1962 and in 1984. A decline in the water level and one depression cone can be seen. The decline in water levels, and the formation of a depression cone, resulted from withdrawals made by 27 wells in the valley. Pumping rates for domestic wells range from 10 to 40 gpm while industrial wells produce from 100 to 800 gpm (including irrigation and mining wells) (Giampaoli, 1986). No other local potentiometric maps are published that show depression cones in areas of ground-water withdrawals, and no injection wells exist in the hydrogeologic study area. Plans for developing large-scale potentiometric maps of the hydrogeologic study area are presented in Section 8.3.1.2.2.

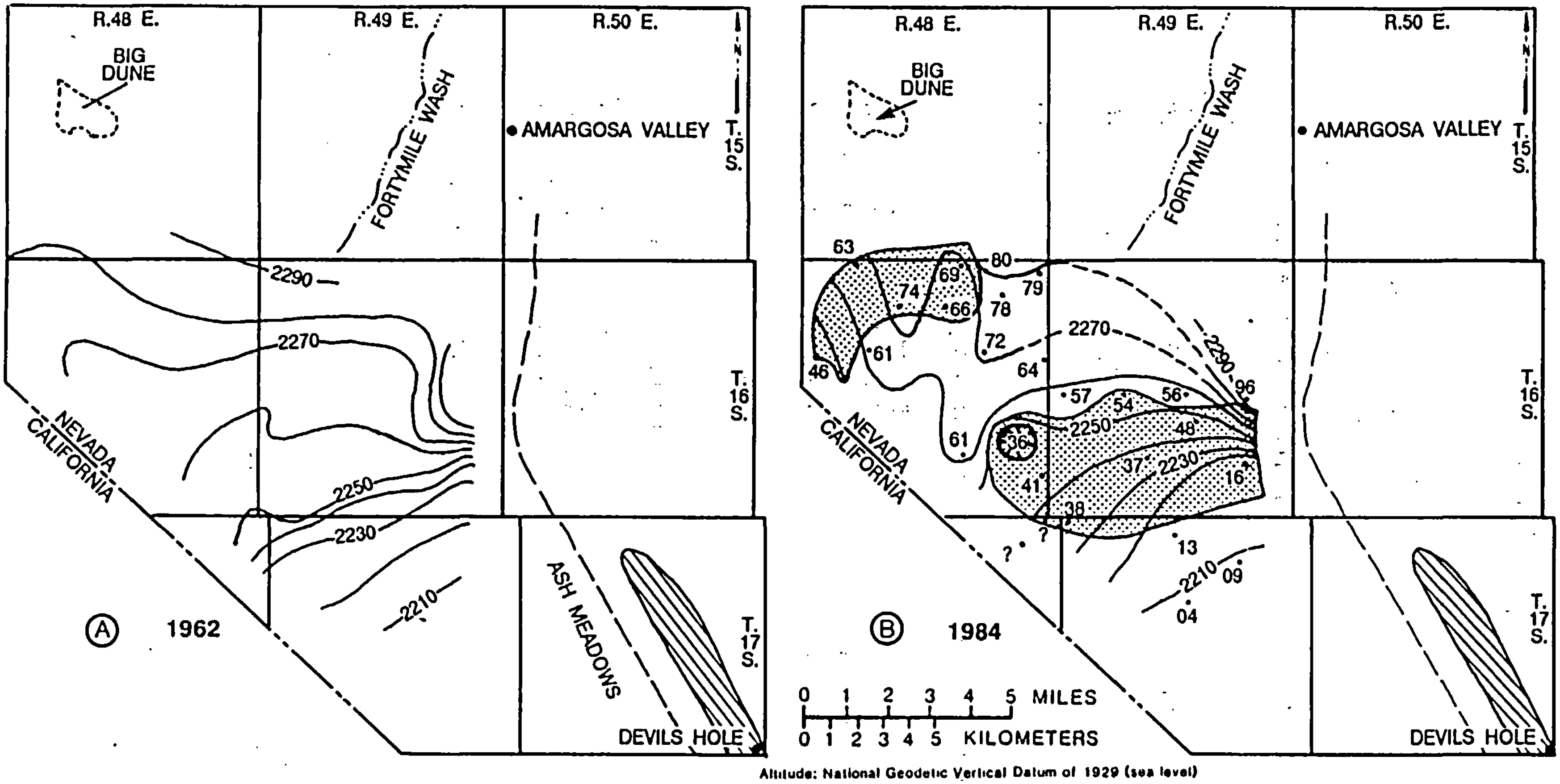
3.8.1.5 Water use for energy development

This section examines water use for the purpose of energy development in the hydrogeologic study area. Only geothermal resource development is considered, because it is the only form of ground-water-related energy development know to be present in southern Nevada.

Table 3-20. Estimated water use for exploratory shaft facilities at Yucca Mountain, Nevada[a,b]

Characterization phase	Amount of water needed (gal)	Amount of water needed (m^3)
PHASE I: SURFACE FACILITY CONSTRUCTION (30 WEEKS)		
Site preparation	15,376,000	5.8×10^4
Facilities construction	1,410,500	5.3×10^3
Pipe cleaning, flushing, testing, and filling	248,500	9.4×10^2
Fire suppression	90,000	3.4×10^2
Subtotal	17,125,000	6.46×10^4
PHASE II: SHAFT SINKING (107 WEEKS)		
Setup, collar, headframe	645,000	2.4×10^3
Shaft sinking and testing	4,962,350	1.9×10^4
Station construction and changeover	2,618,200	9.9×10^3
Raisebore second exploratory shaft	481,050	1.8×10^3
Subtotal	8,706,600	3.31×10^4
PHASE III: TEST CONSTRUCTION AND SUPPORT (174 WEEKS)		
Excavation	10,225,800	3.9×10^4
Construction	835,200	3.2×10^3
Test support	4,614,500	1.7×10^4
Subtotal	15,675,500	5.92×10^4
Total	41,507,100	1.57×10^5

[a]Source: Pedalino (1986).
[b]Includes water for personal use and consumption.



EXPLANATION

— — INFERRED FAULT -- From Winograd and Thordarson (1975, page C70, plate 1); delineated on basis of gravity survey

GENERALIZED AREA OF SPRING DISCHARGE

GENERALIZED AREA WHERE NET WATER-LEVEL DECLINE BETWEEN 1962 AND 1984 EXCEEDED 10 FEET

--2270-- WATER-LEVEL CONTOUR -- Shows altitude of ground-water level in valley-fill deposits. Dashed where approximately located. Contour interval 10 feet. Datum is sea level. Contours for 1962 from Walker and Eakin (1963, plate 3)

• 72 WELL -- Number is water-surface altitude, January 1984, in feet above 2,200 feet (question mark indicates lack of water-level measurement in 1984). Datum is sea level

Figure 3-24. Potentiometric maps of the Amargosa Desert (valley fill aquifer) based on the well data from (1962) (A) and (1984) (B). Modified from Nichols and Akers (1985).

The low-temperature geothermal resources located in the vicinity of Yucca Mountain have little potential for exploitation (refer to Section 1.7 for an evaluation of geothermal resources). The use of these resources for energy development is highly unlikely. Water temperatures measured in test holes in the vicinity of Yucca Mountain are in the range of 50 to 60°C at depths to 1,800 m (5,906 ft) (Craig and Robison, 1984). Current technology requires reservoir temperatures of at least 180°C for commercial power generation (White, 1973). Consequently, it is extremely unlikely that high temperature waters would be present at depths that are economically attractive. Should advances in technology make deeper geothermal resources economically attractive, many areas other than Yucca Mountain could be exploited (Garside and Schilling, 1979).

In summary, there currently is very little potential for geothermal energy resource development within the hydrogeologic study area.

3.8.2 REGIONAL GROUND-WATER MANAGEMENT PLANS

The first part of this section presents an overview of Nevada's philosophy of ground-water management and the measures that are taken to mitigate ground-water supply problems. Agencies involved in the appropriation of ground-water resources and programs or laws that govern ground-water use that might relate to activities at Yucca Mountain are identified. The second part of this section identifies the nearby communities that might be affected as a result of the proposed repository-related withdrawals. Site characterization activities and the construction and operation of a geologic repository at Yucca Mountain would increase the demand for water in the immediate vicinity of the site, as discussed in Section 3.8.1.4. Water use projections for the next 50- and 100-yr periods currently are not available. Data and information that are needed to assess the potential impacts are delineated. Plans for obtaining these data are presented in Section 8.3.1.16.2.

3.8.2.1 Ground-water management in Nevada

Most of the unincorporated communities located within the geohydrologic study area do not have municipal water supply systems. Water use is governed by the appropriate Board of County Commissioners. The State of Nevada, however, has responsibility for protecting its ground-water resources. Areas and communities examined in this section are Pahrump, Beatty, Amargosa Valley, and Area 25 (Figure 3-21) of the NTS; these areas are located proximal to the proposed repository site, or historically have experienced water supply problems. Estimated and projected water use figures for each community located within the hydrogeologic study area are presented in Table 3-21.

Water use in Nevada is governed by the Office of the State Engineer and the Division of Water Resources. Chapter 534 (Title 48-Water) of the Nevada Water Laws outlines and delineates the allowable uses of ground waters. Morros (1982a) presents the laws and statutes relating to all aspects of ground-water and geothermal resources, as described in Chapter 534 and Chapter 534A respectively.

Table 3-21. Existing total water use in the communities located in the hydrogeologic study area

Community	Estimated population 1985[a]	Estimated existing water use (mg/d)[b]	Maximum population increase due to site characterization activities[c]	Projected increase in water use due to site characterization activities[c] (mg/d)
Indian Springs	912	0.8	85	0.07
Indian Springs Air Force Base	900	0.4	ND[d]	ND
Beatty	925[e]	0.8	2	0.002
Mercury	300	0.3	ND	ND
Pahrump	5,500	4.7	127	0.1
Ash Meadows	41	0.04	ND	ND
Johnnie	8	0.007	ND	ND
Amargosa Valley	1,905[f]	1.6	6	0.005
Crystal	65	0.06	ND	ND
Rhyolite	4	0.003	ND	ND
Death Valley Junction	20[g]	0.017	ND	ND
Totals	10,580	8.7	220	0.177

[a]Population data from Smith and Coogan (1984) except where otherwise noted.
[b]mg/d = million gallons per day. Maximum permissible water use in southern Nevada, is 1,800 gal per day per residential unit, or almost 2 acre-feet per year (assuming 2.1 residents per housing unit).
[c]Data from DOE (1986).
[d]ND = no data.
[e]Data from Gram (1985).
[f]Includes population of Amargosa Valley, American Borate Mill, American Borate Housing Complex, and the Spring Meadows area.
[g]Community distribution system. Water quality does not meet U.S. Environmental Protection Agency drinking water standards (French et al., 1984).

The State of Nevada uses a recharge-use philosophy in its management of ground-water resources. As previously discussed in Section 3.8.1, total annual ground-water withdrawals from any given basin may not exceed the perennial yield (Morros, 1982a). Unfortunately there are many difficulties inherent in determining the actual amount of recharge to an undeveloped basin where no pumping has occurred. In many instances, aquifer overdrafts occur before the perennial yield has been firmly established (Todd, 1980).

At the first indication of an aquifer overdraft, measures are taken to carefully regulate ground-water withdrawals. A provision of the Nevada Water Laws grants authority to the State Engineer to designate ground-water basin boundaries in areas where he deems that ground-water resources are being depleted. Such designation orders have been issued in four areas of consideration: (1) the Amargosa Desert ground-water basin, (2) the Pahrump Artesian Basin, (3) Oasis Valley West, and (4) Indian Springs Valley. Designation of a ground-water basin places permits on a preference basis but does not establish which types of permits have priority. Preference is determined on a case-by-case basis by the State Engineer.

3.8.2.2 <u>Local ground-water supply problems</u>

In May of 1979, the State Engineer issued an order designating the Amargosa Desert ground-water basin to prevent further overappropriation of basin ground water. The areas and communities affected by this designation order are Amargosa Valley, rural water users in the Amargosa Desert, and Ash Meadows. Although no order of preference has been established by the State Engineer, permit applications on file for wells located within the Amargosa Desert ground-water basin indicate that irrigation and agricultural use has the lowest preference. New permits for, or changes to domestic and quasi-municipal uses would be favored (Morros, 1982b). Water use at the NTS and the Yucca Mountain site, which are located outside the designated Amargosa Desert ground-water basin boundaries, is not affected by the designation order.

Although water-use in Oasis Valley is currently considered minor (Giampaoli, 1986), the western portion of the Oasis Valley (hydrographic area 228) was designated in 1980 to prevent over appropriation. Recharge to the ground water basin is estimated to be approximately 2,000 acre-feet per year (2.5×10^6 m^3/yr).

The community of Beatty may experience water supply shortages in the near future. Gram (1985) reported that the population growth rate from 1980 to 1985 was nearly 3 percent, while the demand for water had increased nearly 10 percent. Although a high-quality water source has not yet been developed, Gram (1985) has presented several recommendations that could alleviate future water supply problems.

The Indian Springs Valley (hydrographic area 161 in Figure 3-23) was designated in 1980. Water-level declines in the Indian Springs community caused a decrease in local spring discharge (Giampaoli, 1986). Although the amount of water appropriated is minor, total water withdrawals and natural discharge in the form of springs and evapotranspiration are in excess of the perennial yield.

The town of Pahrump, located approximately 100 km southeast of Yucca Mountain, has experienced ground-water overdraft problems in the past. Excessive agricultural withdrawals before 1970 caused a lowering of the water level in the valley fill aquifer. In 1970, the State Engineer ordered a moratorium on the issuance of water permits for irrigation from the Pahrump Artesian basin. Certificated appropriations and development permits for ground water in the Pahrump Valley totaled 90,790 acre-feet (112×10^6 m^3) in 1970, although in recent years actual water withdrawal has averaged approximately 39,720 acre-feet per year (49×10^6 m^3) (DOE, 1986). The repository project probably would not affect the water resources in the Pahrump Valley, since the proposed site is within a different subbasin of the Death Valley ground-water system (Figure 3-23) (Winograd and Thordarson, 1975; Harrill, 1983; French et al., 1984; Waddell et al., 1984).

3.9 SITE HYDROGEOLOGIC SYSTEM

In previous sections of Chapter 3, the regional hydrogeologic setting of Yucca Mountain was considered; this section focuses on the site hydrogeologic system in the immediate vicinity of the site at Yucca Mountain (generally within a few kilometers of the outer boundary of the repository). The site at Yucca Mountain is unique among those being considered in that the repository is intended to be situated deep in the unsaturated zone, about 300 m below land surface and 250 m above the water table (Chapter 6).

The general concept of ground-water flow at Yucca Mountain assumes that a small fraction of the local precipitation enters the unsaturated zone as net infiltration below the surficial plant-root zone, to percolate generally downward and past the repository horizon, and eventually to reach the water table as recharge. Preliminary analyses indicate that temporal variations of net infiltration may be damped out within the uppermost few tens of meters within the unsaturated zone (Weeks and Wilson, 1984; Montazer and Wilson, 1984). Below these depths, moisture flow (net flux) may be under effectively steady-state conditions (Weeks and Wilson, 1984; Klavetter and Peters, 1986). Because net infiltration is irregularly distributed over the surface of Yucca Mountain and because the hydrologic properties within the unsaturated zone are heterogeneous, considerable spatial variability in flux probably occurs at any horizon within Yucca Mountain, including the repository (Montazer and Wilson, 1984).

Recharge at Yucca Mountain joins and moves laterally through the saturated-zone ground water, whose likely sources of recharge are the mountainous highlands north of the site (although there may be some recharge that is more local; see Section 8.3.1.2.1 for plans to evaluate possible recharge along Fortymile Wash). Ground water arriving at the water table beneath Yucca Mountain probably mixes with ground water in the saturated zone only within the upper few hundred meters of saturated Tertiary tuffs, regardless of the particular hydrogeologic units along the flow path. This occurs because vertical hydraulic gradients within this interval are small, and potentiometric heads at greater depth in less permeable rocks of Tertiary and

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 DOE/RW-0160

Nuclear Waste Policy Act
(Section 113)

Consultation Draft

Site Characterization Plan

Yucca Mountain Site, Nevada Research and Development Area, Nevada

Volume II

January 1988

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
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DOCUMENT ORGANIZATION

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Chapter 3

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Paleozoic age are significantly greater than the water table. At least within the upper part of the saturated zone, the water moves south or southeast from Yucca Mountain.

The rocks underlying Yucca Mountain through which the ground water moves are mostly fractured tuffs of Tertiary age; the major stratigraphic units are shown in a schematic geologic section in Figure 3-25. Because physical properties of the rocks that are believed to control movement of ground water in the unsaturated zone are not completely consistent with stratigraphic boundaries, hydrogeologic boundaries for the unsaturated zone have been defined and are shown in Table 3-22.

An understanding of the saturated-zone hydrologic system is required for waste isolation because this zone contains substantial portions of many pathways to the accessible environment. An understanding of saturated-zone hydrology is also needed in order to evaluate the hydrologic effects of future climate changes; these effects include potential rises in the water table and changes in gradients and paths of ground-water flow in the saturated zone. The distributions of critical parameters, such as effective porosity, are presently unknown and will be evaluated by future testing programs (Section 8.3.1.2.3).

This section describes monitoring networks, from which the following baseline hydrologic data are being obtained: potentiometric levels; hydraulic characteristics of the formations that may store and transmit water in the unsaturated and saturated zones; conceptual ideas of modes and flow paths of ground water, including recharge and discharge; hydrochemistry, ground-water age, and hydraulic parameters as indicators of ground-water velocity and travel times; local ground-water uses that could affect the natural flow system; and past hydrogeologic conditions, to the extent that an understanding of them may be helpful for prediction of future conditions.

Because of the need to emphasize the unsaturated zone at Yucca Mountain, hydrogeologic characterization of the site poses a dual problem. Specifically, it is necessary (1) to define the macroscopic hydrologic system within the unsaturated zone and (2) to describe this system in terms of the microscopic hydrologic processes that occur within the thick sequence of welded and nonwelded, fractured and unfractured tuffs that make up the unsaturated zone. The fundamental concepts and theory of moisture flow and storage within variably saturated natural media have been developed for specific application to problems of soil physics (Hillel, 1980), petroleum-reservoir engineering (Amyx et al., 1960) and geothermal resource evaluation (Faust and Mercer, 1977). The resultant generally considered theory may not be applicable to indurated tuffs that have low porosity and low permeability and that also may be highly fractured. Consequently, a complete characterization of the site hydrologic system must examine the mechanisms by which moisture can be stored and transported within the fractures and interstices of deeply buried tuffs. Only then can a set of hypotheses be developed to construct a macroscopic conceptualization within which these mechanisms act to determine the present, naturally occurring hydrologic system.

A major part of the site characterization program for the unsaturated zone, as described in Section 8.3.1.2.2, is devoted to field, laboratory, and theoretically based studies to test various concepts and hypotheses for

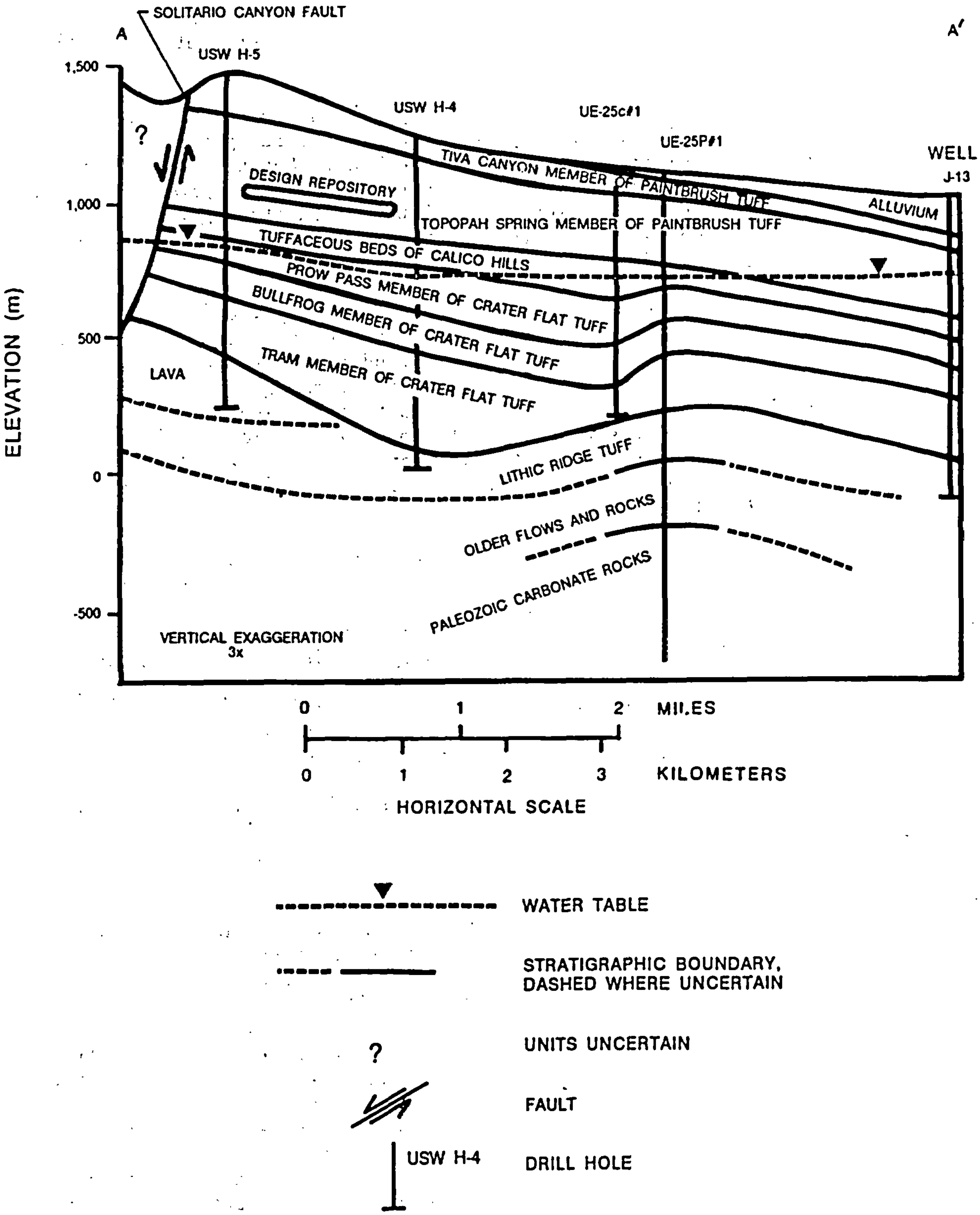


Figure 3-25. Simplified stratigraphy of section across Yucca Mountain showing stratigraphic relationships (see Figure 3-28 for location of section).

Table 3-22. Definition of unsaturated-zone hydrogeologic units and correlation with rock-stratigraphic units[a].

Rock-Stratigraphic Unit		Hydrogeologic Unit	Approximate Range of Thickness (m)	Lithology[b]
Alluvium		QAL	0-30	Irregularly distributed surficial deposits of alluvium and colluvium
Paintbrush Tuff	Tiva Canyon Member	TCw	0-150	Moderately to densely welded, devitrified ash-flow tuff
Paintbrush Tuff	Yucca Mountain Member	PTn	20-100	Partially welded to nonwelded, vitric and occasionally divitrified tuffs
Paintbrush Tuff	Pah Canyon Member	PTn		
Paintbrush Tuff	Topopah Spring Member	TSw	290-360	Moderately to densely welded, devitrified ash-flow tuffs that are locally lithophysae-rich in the upper part, includes basal vitrophyre
Tuffaceous beds of Calico Hills		CHn (CHnv, CHnz)	100-400	Nonwelded to partially welded ash-flow tuffs; Vitric (CHnv) / Zeolitized (CHnz)
Crater Flat Tuff	Prow Pass Member	CHn (CHnv, CHnz)		
Crater Flat Tuff	Bullfrog Member	CFu	0-200	Undifferentiated, welded and nonwelded, vitric, devitrified, and zeolitized ash-flow and air-fall tuffs

[a]Sources: Montazer and Wilson (1984) and as noted in footnotes.

[b]Lithology summarized from Ortiz et al. (1985).

QAL - Quaternary Alluvium
TCw - Tiva Canyon welded unit
PTn - Paintbrush nonwelded unit
TSw - Topopah Spring welded unit
CHn - Calico Hills nonwelded unit
CHnv - Calico Hills nonwelded vitric unit
CHnz - Calico Hills nonwelded zeolitized unit
CFu - Crater Flat undifferentiated unit

moisture flow in fractured tuffs. These studies are to be combined with large-scale field and mathematical-modeling studies to further develop and test conceptualizations of the overall macroscopic hydrologic system. To establish an internally consistent conceptual framework and terminology, the conventional theory of moisture flow and storage in variably saturated porous media is reviewed in the following paragraphs, together with some of its potential limitations and inadequacies with respect to conditions thought to prevail at the Yucca Mountain site.

The term moisture is introduced here in a generic sense to include both liquid water and water vapor. Moisture flow and storage, thus, include the combined flow and storage of liquid water and water vapor. Under partially saturated conditions, water vapor will be present within the pore gas, regarded as a mixture of air and water vapor. Under most natural conditions, water vapor and liquid water will be in local thermodynamic phase equilibrium within the pore and fracture space. In partially saturated porous media, the equilibrium vapor pressure is a function of both temperature and matric potential and at constant temperature decreases with decreasing saturation (Hillel, 1980). Liquid-water movement in a partially saturated porous medium is described usually by Darcy's law, whereas water-vapor movement proceeds either as molecular diffusion under a water-vapor concentration gradient or by advection accompanying bulk pore-gas flow.

Unless specified otherwise, saturation refers to liquid-water saturation, S_ℓ, and is defined to be the fractional pore volume or fracture space occupied by liquid water. Saturation and other bulk hydrologic properties are meaningful only when defined as averages over volumes of rock sufficiently large to enclose many pores or fractures (over which the saturation and other bulk hydrologic properties may be taken to be averaged) but yet must be small compared with the overall size of the macroscopic hydrologic system. Because representative linear pore dimensions are of the order of 1 micrometer (Peters et al., 1984) or less, while representative fracture spacings are of the order of 5 cm or more (Scott et al., 1983), a considerable difference may exist in the scale of (1) the bulk-rock volume appropriate for defining the rock-matrix hydrologic properties, which are averaged over the pore space, and (2) the volume containing many fractures that is required to define the bulk properties for the fractures. Under these conditions, the pores and fractures may effectively define two overlapping continuum systems, each regarded as an equivalent porous medium. Such a double-porosity model may be appropriate, for example, to describe a highly fractured but otherwise homogeneous tuff in which the fractures bound distinct rock-matrix blocks. At the opposite extreme, the fracture density may be so low that bulk fracture properties cannot be defined meaningfully, in which case the fractures that are present would have to be regarded as discrete entities. Such may be the case in an otherwise unfractured hydrogeologic unit that is transected by a fault.

Under partially saturated conditions, liquid water is bound to the solid within the pore and fracture openings either by surface-tension (capillary) forces or, at very low saturations, by physical or chemical adsorption. The strength of the bonding force is measured in terms of an equivalent negative pressure, or pressure head, here designated the matric potential. In a fractured medium, the matric potential within the fractures need not be equal to that within the enclosing rock matrix, although pressure equilibration will tend to be established over time. Large differences in matric potential between rock matrix and fractures may occur under transient conditions, for example, within and following an advancing infiltration front, and thus may affect significantly moisture movement under such conditions (Klavetter and Peters, 1986).

Matric potential is a function of liquid-water saturation, and an analytic or graphical representation of the functional relation defines the moisture-retention curve for the porous medium. Moisture-retention curves for most media are not unique; they display hysteresis in which the precise relation between matric potential and saturation depends on whether saturation is increasing (wetting curve) or decreasing (drying curve). Standard techniques, using mercury intrusion, pressure-plate apparatus, thermocouple psychrometers, and centrifuges have been developed (Hillel, 1980) by which to measure the moisture-retention curves for small soil or rock samples. The intact-fracture test within the exploratory shaft (Section 8.3.1.2.2) is designed, in part, to investigate the moisture-retention properties appropriate to discrete fractures.

The vector volumetric flux of liquid water moving under isothermal conditions through a partially saturated, natural hydrogeologic unit, regarded as an equivalent porous-medium continuum system, is generally presumed to be determined by the spatial gradients of matric and gravitational potentials and by the hydrologic properties. This functional dependence is expressed mathematically by the Darcy's law for unsaturated liquid-water flow, one version of which may be written as (Hillel, 1980):

$$q_\ell = -K_\ell \, K_R \, \mathrm{grad} \, (\psi_\ell + z), \qquad (3\text{-}3)$$

where

q_ℓ = volumetric flux of liquid water (L^3/L^2T)

K_ℓ = saturated (liquid) hydraulic conductivity (L/T)

K_R = relative hydraulic conductivity (dimensionless)

ψ_ℓ = capillary-pressure head (L)

z = vertical coordinate (positive upward) relative to a specified x and y-coordinate plane (L)

grad = $i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$, where i, j, and k are unit vectors aligned with the x-, y-, and z-coordinate axes, respectively (1/L).

In a fractured medium under the dual-porosity model, identical versions of Equation 3-3 would apply separately to the rock-matrix and fracture systems with q_ℓ, ψ_ℓ, K_ℓ, and K_R defined appropriately for these two distinct systems.

The saturated hydraulic conductivity, K_ℓ, entering Equation 3-3 may be expressed in terms of the intrinsic permeability, k, of the medium as (Hillel, 1980):

$$K_\ell = \frac{k\rho_\ell g}{\mu_\ell}, \tag{3-4}$$

where

k = intrinsic permeability (L^2)

ρ_ℓ = liquid-water mass density (M/L^3)

g = gravitational acceleration (L/T^2)

μ_ℓ = liquid-water viscosity (M/LT).

The medium is (hydrologically) homogeneous if k and K_ℓ are spatially invariant and is isotropic if k and K_ℓ are independent of direction. In general, k and K_ℓ are assumed to vary stochastically within an otherwise homogeneous natural medium with mean values that are spatially invariant to within some statistically definable limits of uncertainty (Dettinger and Wilson, 1981; Travis, 1986). These mean values constitute one basis on which to identify and discriminate between distinct hydrogeologic units. The parameters k and K_ℓ are likely to be anisotropic in layered media, such as bedded tuffs, and in fractured media in which the resultant directional dependence is determined by the geometry of the fracture network.

The relative hydraulic conductivity, K_R, is defined as the ratio of hydraulic conductivity at a given matrix saturation to that at complete matrix saturation (K_ℓ). The parameter, K_R, is of unit magnitude at complete saturation and, usually, decreases rapidly towards zero with decreasing saturation or, equivalently, matric potential. Because the functional dependence of K_R on S_ℓ, or ψ_ℓ, is difficult to determine through direct measurement, procedures have been developed for soils by which to infer closed-form analytic representations for this dependence from the corresponding moisture-retention curve (Brooks and Corey, 1964; Mualem, 1976; van Genuchten, 1980). It is not clear that these approximating representations are appropriate to indurated fractured tuffs, but they have been used in preliminary studies at Yucca Mountain (Klavetter and Peters, 1986; Rulon et al., 1986) in lieu of more fundamental data. That this approach is appropriate to describe the rock-matrix properties is supported indirectly in that the moisture-retention curves measured on individual samples of tuff can be fitted accurately, for example, by the analytic representation developed for soils by van Genuchten (1980). Fractured-rock systems introduce further complications that depend on the mechanisms by which moisture is transported in partially saturated fractures and define an area of current active research (Montazer and Harrold, 1985; Wang and Narasimhan, 1985). The bulk-permeability test to be conducted within the exploratory shaft (Section 8.3.1.2.2) is intended to obtain direct empirical data on the bulk hydrologic properties for the unsaturated, fractured Topopah Spring welded unit.

The moisture-retention curve together with the dependence of relative hydraulic conductivity on saturation or, equivalently, matric potential, constitute the set of moisture-characteristic relations for a particular porous medium under partially saturated conditions. Consequently, these relations must be supplied as part of the suite of hydrologic-property data for each hydrogeologic unit within the unsaturated zone at Yucca Mountain. A hydrogeologic unit, in this usage, is defined to be a functional unit composed of an interval or volume of rocks within which the mean hydrologic properties are effectively spatially invariant. A hydrogeologic unit may include, in whole or in part, one or more rock-stratigraphic units.

In addition to the storage and transport of moisture as liquid water within the unsaturated zone, moisture may be stored and transported as water vapor within the air-filled pore space. The bulk flow of air in pores and fractures probably is usually regarded to be Darcian in which the appropriate potential is the local pore-gas pressure. Gas flow is more complex, however, because the compressibility of the gas must be taken into account through an appropriate equation of state. Furthermore, in pores and fractures whose apertures are a few times the mean free path of pore-gas molecules, the gas will tend to slip past the pore and fracture walls to produce an effective increase of gas permeability k_g according to the law $k_g = k\ (1 + b/P)$ (Klinkenberg, 1941), where k is the (intrinsic) permeability of the medium, P is the ambient pore-gas pressure, and b is an empirical constant appropriate to the pore-gas system under consideration. For example, Reda (1985a) determined experimentally that the permeability with respect to nitrogen gas of a sample of the TSw unit was a strongly dependent function of pore-gas pressure for which the Klinkenberg constant b = 0.76 MPa.

Not only does bulk-gas flow and storage need to be considered in order to assess the efficacy of vapor-phase moisture transport within the unsaturated zone at Yucca Mountain; but also, air is a very convenient fluid medium to use in field determinations of permeability by monitoring both barometrically induced pressure changes with depth in wells (Weeks, 1978) and the response in observation wells due to air injection within packed-off zones in neighboring test wells. The monitoring and mathematical modeling of gas-tracer distribution and movement (using both environmental and introduced tracers) yield information on the overall pore-gas flow system from which inferences pertaining to the liquid-water system may be drawn (Section 3.9.1.3.).

The division of the unsaturated zone at Yucca Mountain into hydrogeologic units is a first step in defining the macroscopic hydrologic system at the site. As described in Section 1.2.2, and depicted in Figure 3-26, Yucca Mountain is composed of a stratified sequence of Tertiary volcanic rocks consisting of ash flow and ash-fall tuffs that, at land surface, are overlain by irregularly distributed deposits of alluvium and colluvium. The division of this sequence into hydrogeologic units as described here is based on the divisions developed by Montazer and Wilson (1984) and by Ortiz et al. (1985) and is shown correlated with formal rock-stratigraphic units (Chapter 1) in Table 3-22. The hydrogeologic units are identified in Table 3-22 by symbols such as TSw, and these symbols are used to designate hydrogeologic units in subsequent discussions of the unsaturated zone to distinguish clearly between hydrogeologic and rock-stratigraphic units. The symbol QAL indicates alluvium, TCw indicates the Tiva Canyon welded (hydrogeologic)

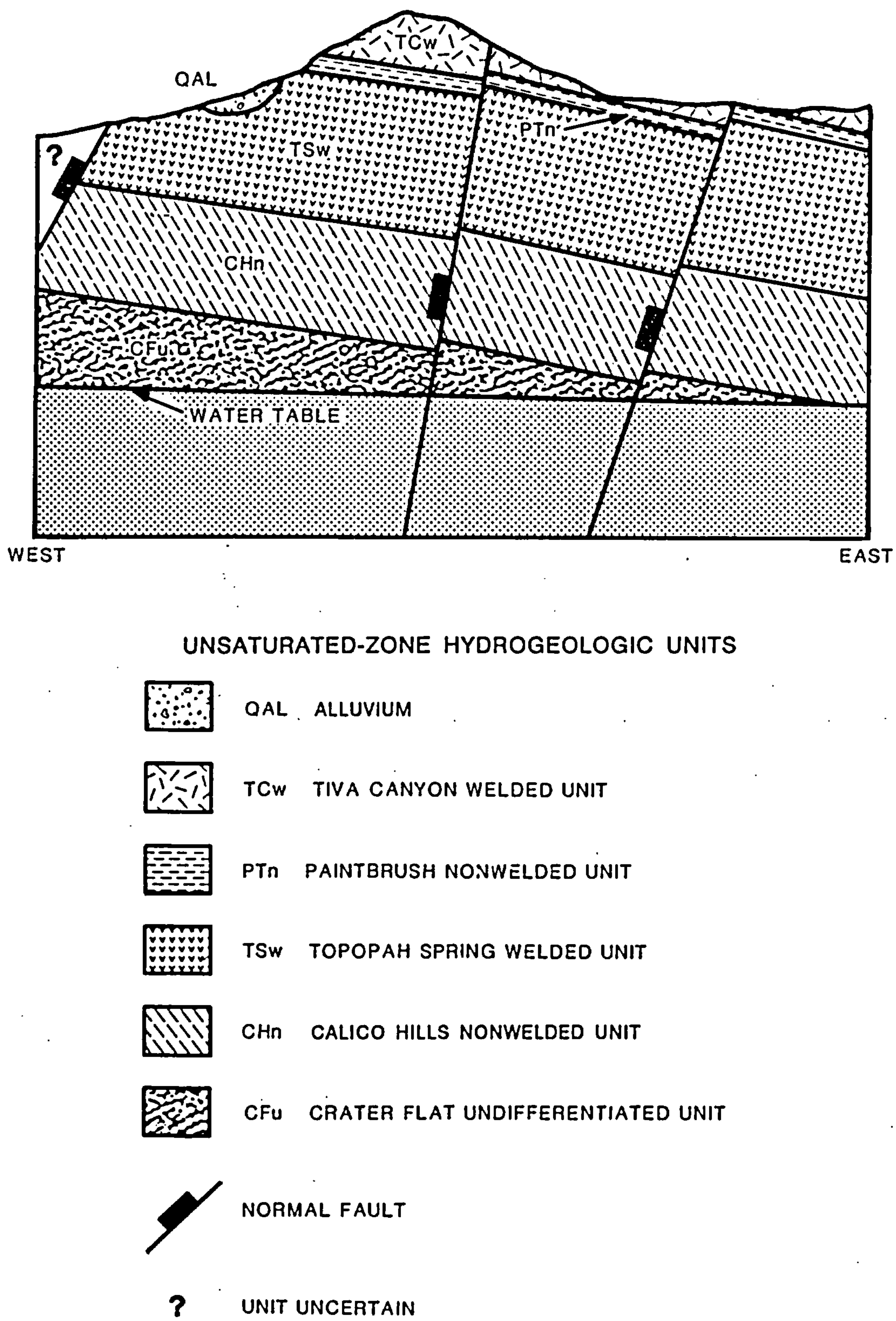


Figure 3-26. **Conceptual east-west hydrogeologic section through the unsaturated zone at Yucca Mountain. Modified from Montazer and Wilson (1984).**

unit, PTn indicates the Paintbrush nonwelded unit, TSw indicates the Topopah Spring welded unit, CHn indicates the Calico Hills nonwelded unit (with "v" indicating the vitric facies and "z" indicating the zeolitic facies), and CFu indicating the Crater Flat unit.

Each of the individual hydrogeologic units listed in Table 3-22 belongs to one of three broadly based hydrogeologic rock types distinguished qualitatively as follows (the values given for saturated matrix hydraulic conductivity and for fracture density are taken from Section 3.9.2.1):

1. Densely to moderately welded tuffs that are highly fractured. This group includes units TCw and TSw of Table 3-22 and is characterized by low saturated hydraulic conductivity of the rock matrix (about 1 x 10^{-11} m/s) and relatively high fracture densities (about 10 to 40 fractures/m^3). Under fully saturated conditions, the fracture hydraulic conductivity probably exceeds that of the rock matrix by several orders of magnitude. The rocks of this group are characterized by relatively low matrix porosities of about 10 percent.

2. Nonwelded vitric tuffs containing few fractures. This group includes the PTn and CHnv units of Table 3-22 and is characterized by relatively high saturated hydraulic conductivity of the rock matrix (about 10^{-8} to 10^{-6} m/s) and low fracture densities (1 to 3 or fewer fractures/m^3). These rocks have relatively high matrix porosities (about 30 to 45 percent).

3. Nonwelded zeolitized tuffs containing few fractures. The prototype example is the CHnz unit of Table 3-22, which has a saturated hydraulic conductivity of about 10^{-11} m/s or less, a fracture density of 1 fracture/m^3 or less, and a matrix porosity of about 30 percent. A tuff sample need not be completely zeolitized to belong in this classification. The tuffs in CHnz range from partially to completely zeolitized but are grouped into this one rock type when their hydrologic properties are similar.

The hydrologic properties of the hydrogeologic units are discussed in greater detail in Section 3.9.2.1.

The formulation of a conceptual model of a natural process or phenomenon is the essence of scientific method that according to Russell (1948), "consists in inventing hypotheses which fit the (available) data, which are as simple as is compatible with this requirement, and which make it possible to draw inferences subsequently confirmed by observation." In general, the conceptual model of a natural hydrologic system considers the macroscopic configuration and state of the system together with the microscopic hydrologic processes operating within it.

Generalized conceptual models for the hydrologic system within the unsaturated zone at Yucca Mountain have been presented by Montazer and Wilson (1984) and Sinnock et al. (1986). The geologic framework underlying these conceptualizations is illustrated schematically in Figure 3-26, which depicts a generalized east-west cross section through the Yucca Mountain block at the repository site (Figure 3-25).

As depicted in Figure 3-26, the geologic framework for the hydrologic system within the unsaturated zone is defined by a block of layered, east-dipping hydrogeologic units that is bounded above by land surface, below by the water table, laterally on the west by a west-dipping normal fault, and laterally on the east by one or more west-dipping normal faults. In addition, the interior of the block may be transected by one or more high-angle faults (e.g., the Ghost Dance fault) across which hydrologic properties may change abruptly. In addition, the bounding and internal faults may act preferentially either as conduits for or as barriers against moisture flow. The processes of moisture flow that are envisioned to be occurring or that could occur under natural conditions within this macroscopic system are described and evaluated in terms of currently available data in Section 3.9.3.4.

3.9.1 BASELINE MONITORING

Baseline monitoring is an engineered system for continuing measurement of existing ground-water conditions that will serve as an historical data base for future observational comparison. Long-term monitoring of potentiometric levels and hydrochemistry may demonstrate the degree of stability of the geohydrologic system during the period required for waste isolation. In addition, water-level observations would record any changes of the water table that would affect the overall ground-water travel time in both the unsaturated and saturated zones beneath the repository.

Eight monitoring boreholes have been drilled into the unsaturated zone (Figure 3-27). Of these only one, drillhole USW UZ-1, located north of the Yucca Mountain site, is currently being monitored. Ten additional boreholes will be included in the unsaturated-zone monitoring network (Section 8.3.1.2.2). Monitoring will be accomplished with a variety of instruments permanently emplaced at various levels within these boreholes. These instruments will be connected to an automatic data acquisition system on the ground surface. Data collected during monitoring will include downhole temperature, pneumatic pressure, matric potential, and pore gas sampling for hydrochemical analysis. The instrumentation to be installed within the boreholes is designed to permit monitoring to continue for an indefinite period of time after the site characterization program has been completed, as required for performance confirmation.

Based on observations of instrument performance and analysis of data collected from drillhole USW UZ-1, the concept of long-term monitoring within the unsaturated zone in deep boreholes appears tenable. After more than 2 yr of monitoring, the majority of the instruments installed in drillhole USW UZ-1 were still functioning and producing reasonable data (Montazer et al., 1985). Considerable experience in instrumenting a deep borehole and in assessing ambient conditions within the unsaturated zone at Yucca Mountain was gained from the trial instrumentation of drillhole USW UZ-1. This experience will be applied to the instrumentation of the remaining boreholes (Section 8.3.1.2.2).

A network of 25 test holes exists from which water-level measurements of the saturated zone are obtained (Figure 3-28). Ten of the holes are

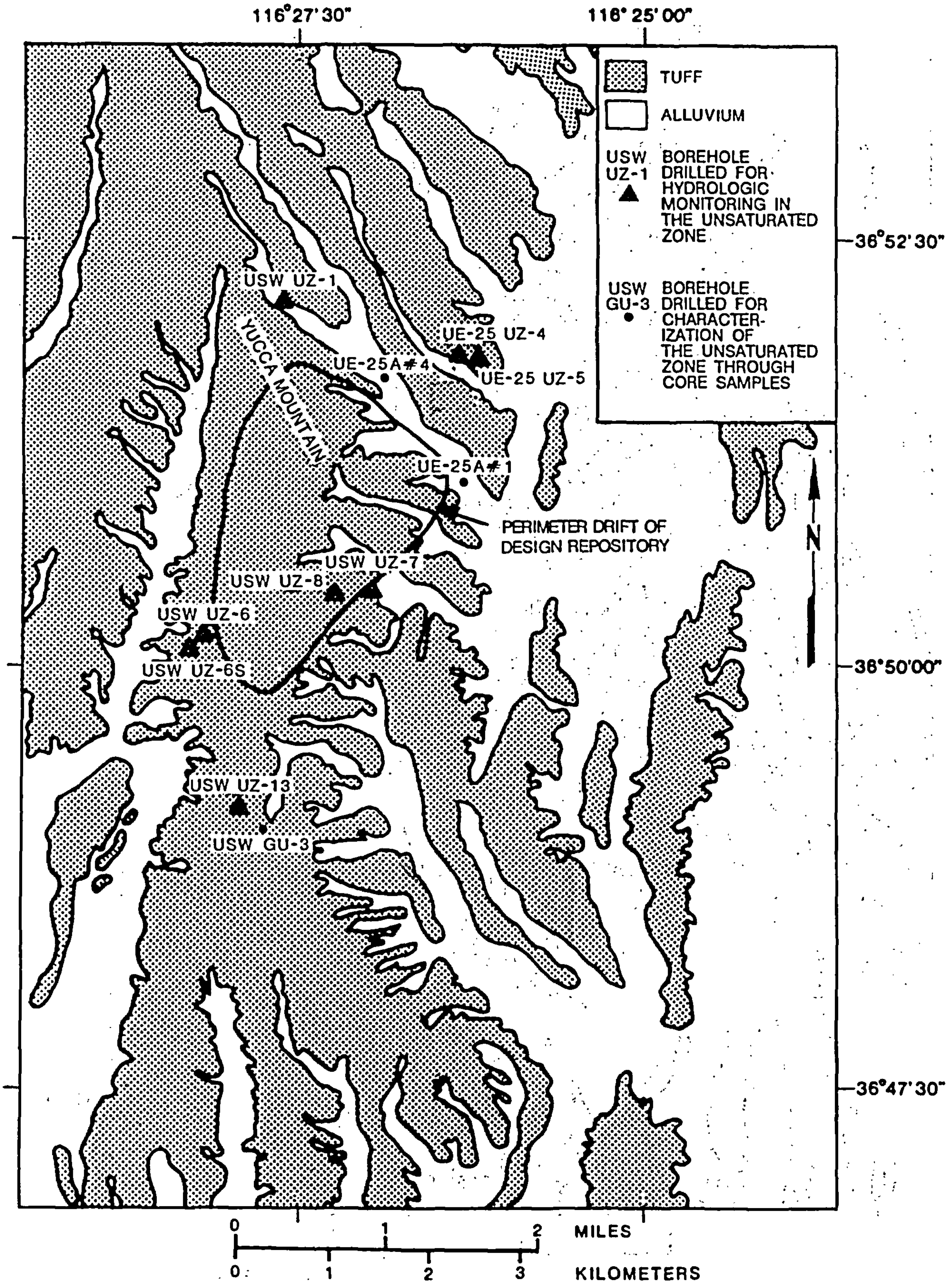


Figure 3-27. Locations of drilled monitoring boreholes and core sampling boreholes in the unsaturated zone at Yucca Mountain.

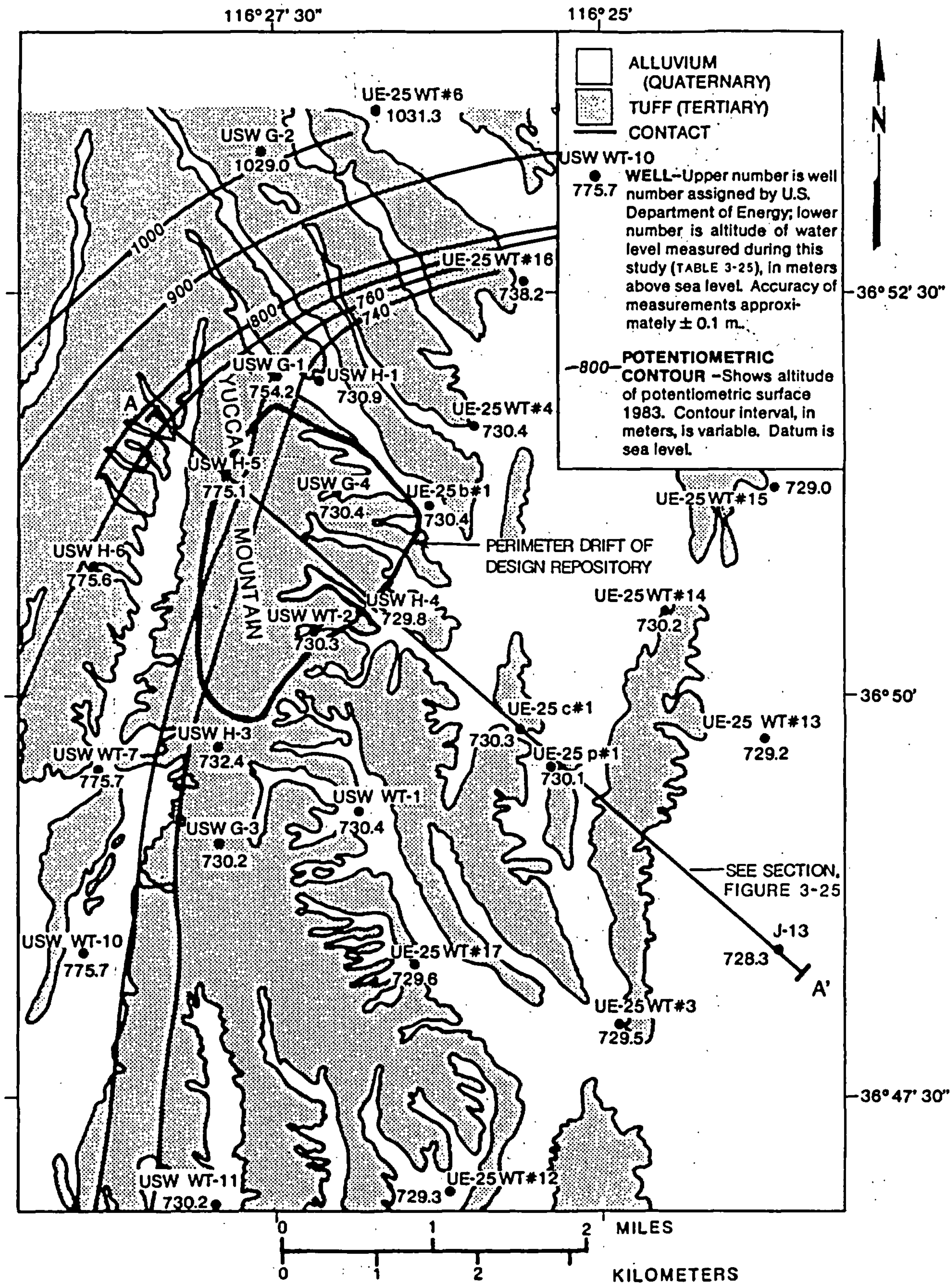


Figure 3-28. Preliminary composite potentiometric-surface map of the saturated zone. Yucca Mountain. Modified from Robison (1986).

monitored continuously, and the remainder are measured periodically. Those being measured periodically are being converted to continuous monitoring. At least 8 additional water-table drillholes are planned to define further the gradient of the potentiometric surface (Section 8.3.1.2.3.1). Observation of small water-level changes is difficult because depths to water at Yucca Mountain are great, ranging from about 300 to 750 m below land surface (Robison, 1986), and because the changes are small relative to the measuring precision attainable. Based on available data, it can be concluded that seasonal variations in water levels probably are a fraction of a meter, and no long-term trends have been discerned yet.

3.9.1.1 Monitoring networks

This section describes the monitoring wells currently in existence in the unsaturated and the saturated zones at Yucca Mountain.

3.9.1.1.1 Unsaturated zone

Monitoring of ambient hydrologic conditions in the unsaturated zone is an important component of the planned hydrogeologic investigations for site characterization at Yucca Mountain. The monitoring program, both present and planned, is designed to quantify the energy status of the variably saturated rock-water system at Yucca Mountain. Moisture flux, whether under saturated or unsaturated flow conditions, cannot be measured directly and must be calculated from measured values of hydraulic conductivity and total potential gradient along the path of flow. Fluid potentials that govern variably saturated two-phase (liquid and gas) flow are as follow: (1) matric potential for the liquid phase; (2) gravitational potential; (3) gas-phase pressure, or pneumatic potential; (4) osmotic potential; and (5) thermal potential. In situ borehole monitoring at Yucca Mountain is designed to measure directly these potentials (except the gravitational potential, which is given directly by the height of the monitoring point above some arbitrarily selected datum). Laboratory testing of core and in situ pneumatic testing before instrumenting the boreholes are the means by which hydraulic conductivities (under various degrees of saturation) are obtained in order to calculate moisture and gas fluxes once the potential gradients are known. Plans for these testing programs are described in Section 8.3.1.2.2.

Hydrologic conditions within the unsaturated zone at Yucca Mountain are presently being monitored only in drillhole USW UZ-1 (Figure 3-27), which was completed in November 1983. This drillhole was drilled without water using a reverse air vacuum system to minimize disturbing local hydrologic conditions near the borehole (Whitfield, 1985). It was drilled to a total depth of 387 m, whereupon drilling was discontinued because an apparent perched-water zone was encountered. However, because the water was contaminated with the drilling-fluid polymer used to drill drillhole USW G-1, located 305 m from drillhole USW UZ-1, it was speculated that the perched-water horizon was not natural but a result of drilling drillhole USW G-1 (Whitfield, 1985). Following drilling and geophysical logging, drillhole USW UZ-1 was instrumented at 33 depth levels over a total depth of 371 m (Montazer et al., 1985). At

15 of these levels, 3 well screens were embedded in dry, coarse-sand columns that were isolated from each other by thin layers of bentonite, columns of silica flour, and isolation plugs consisting of expansive cement. The upper and lower screens within each of these 15 levels were equipped with access tubes for gas sampling. Thermocouple psychrometers to measure matric potential were emplaced in the upper and middle screens and pressure transducers to measure pore-gas pressure in the middle and lower screens at each level. In addition to these instruments, 18 heat-dissipation probes, which also measure matric potential, were installed within the columns of dry silica flour. Six of the heat-dissipation probe stations were also equipped with thermocouple psychrometers. The configuration of the completed borehole and the location of the 33 instrument stations within the borehole are shown in Figure 3-29a and 3-29b. The operation and calibration of the thermocouple psychrometers and the heat-dissipation probes are described by Thamir and McBride (1985). Thermocouple psychrometers measure matric potentials over the range from -4.5 to -75 bars (-0.5 to -7.5 MPa), whereas the useful range of the heat dissipation probes is from -0.1 to -5 bars (-0.01 to -0.5 MPa) (Thamir and McBride, 1985). All instruments were connected to an automatic data-acquisition system installed at land surface. Data loggers were programmed to take hourly readings of the thermocouple psychrometers and twice daily readings of the heat-dissipation probes during the first 50 days of operation, after which the thermocouple psychrometers were read twice daily and the heat-dissipation probes once daily. The pressure transducers and thermocouples were sampled twice hourly during the first 90 days of operation and, subsequently, have been sampled every 2 h (Montazer et al., 1985).

The results of monitoring in borehole USW UZ-1 are described in a detailed report by Montazer et al. (1985). Preliminary findings indicated that after more than two years of regular monitoring, most of the instruments were still functioning and producing reasonable data.

Several operational problems were identified during the 2-yr trial monitoring period. These included possible long-term drift of the pressure transducers, long equilibration times for the thermocouple psychrometers placed in the dry, silica-flour columns, and frequency of failure of the heat-dissipation probes. Data from drillhole USW UZ-1 indicate that the gas-sampling program has had a positive effect on minimizing the equilibration time for psychrometers in screens equipped with gas sampling access tubes. Apparently, the periodic withdrawal of formation gas across the initially dry, coarse-sand columns decreased the time needed to establish moisture equilibrium between the instrument chamber and host formation. These equilibration problems will be addressed during site characterization (Section 8.3.1.2.2).

In addition to the continued matric-potential, gas-pressure, and gas-sampling monitoring at drillhole USW UZ-1, an expanded network of monitoring boreholes is planned (Section 8.3.1.2.2) to enlarge the areal and vertical coverage of ambient and changing hydrologic conditions within the unsaturated zone. Deep boreholes that penetrate the tuffaceous beds of Calico Hills are to be drilled north, east, south, and west of the repository block. The remaining boreholes are intended to penetrate the uppermost Topopah Spring Member of the Paintbrush Tuff and will be used to assess the rate and spatial distribution of net infiltration. Eight wells of this network have been

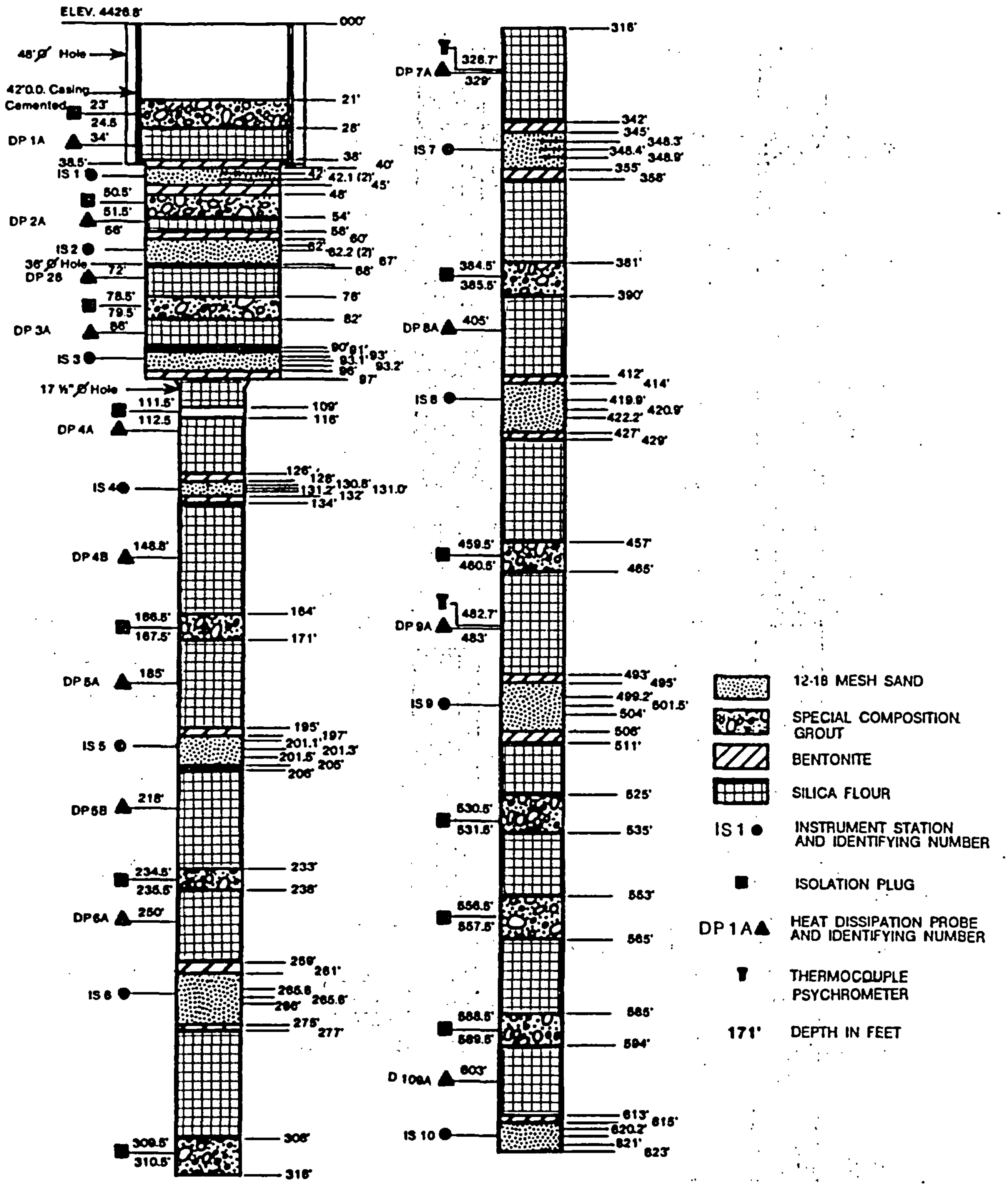


Figure 3-29a. Instrumentation of monitoring borehole USW UZ-1 (0- to 623-feet depth). Modified from Montazer et al. (1985).

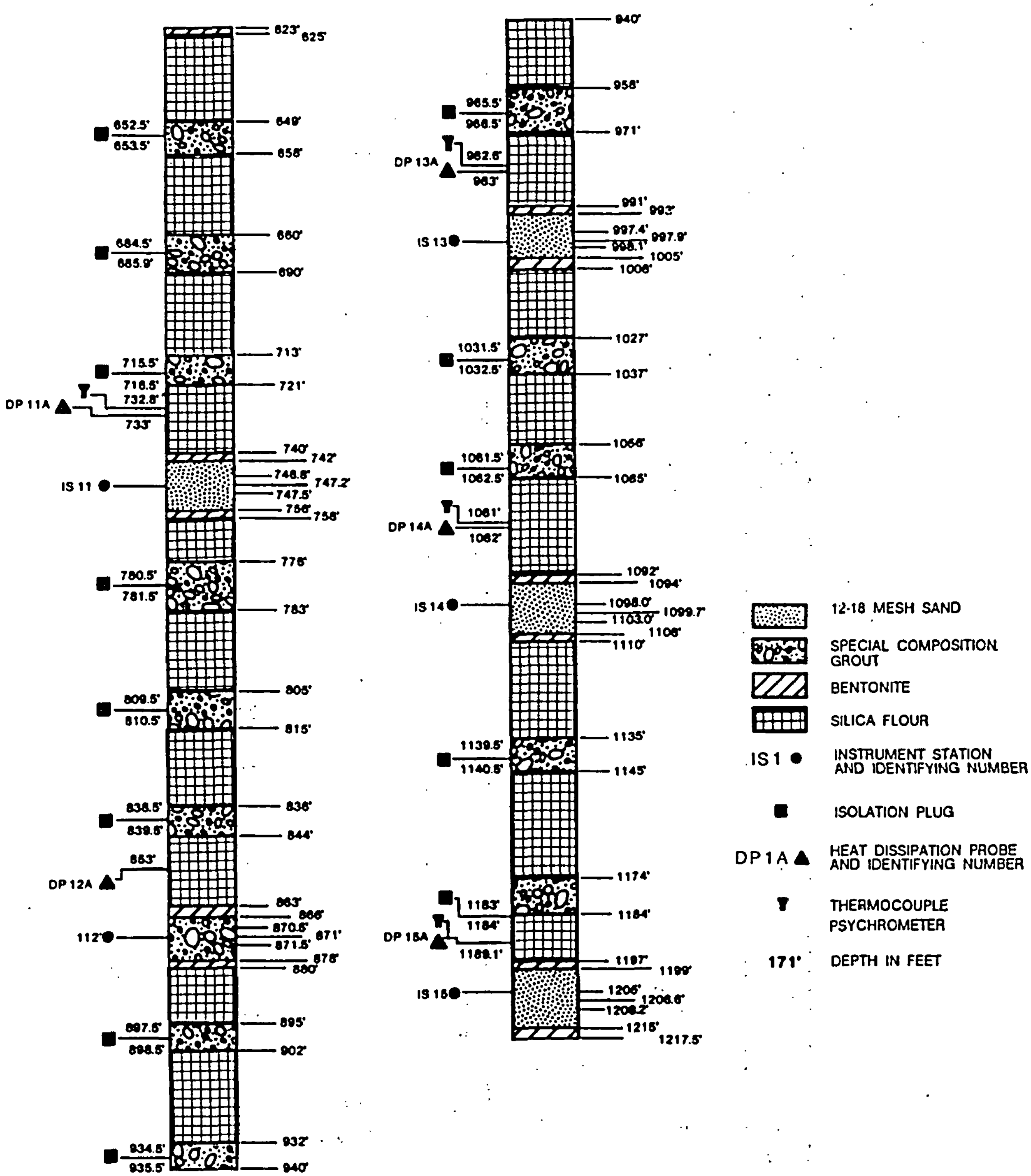


Figure 3-29b. Instrumentation of monitoring borehole USW UZ-1 (623-1217.5 feet depth). Modified from Montazer et al. (1985).

drilled but not instrumented. These wells are listed in Table 3-23 and their locations shown in Figure 3-27.

3.9.1.1.2 Saturated zone

As indicated in Section 3.9.1, water-level measurements presently being made provide a foundation for a monitoring program. The monitored sites (most of those shown on Figure 3-28 are part of the monitoring program) include two geologic test holes, which were drilled as deep as 1,800 m to obtain data on lithology and stratigraphy; seven hydrologic test holes, in which pumping and other tests were performed to determine hydraulic characteristics of the formations; and 14 water-table holes, which were planned to penetrate the water table only a minimum amount. The water-table holes are areally distributed to enable definition of the potentiometric surface at Yucca Mountain so that gradients and probable flow paths can be determined. Additional water-table holes are planned to be drilled and monitored (Section 8.3.1.2.3.). The planned principal purpose of the drillholes now being observed was not for baseline monitoring, and there was no formal selection process for their locations or depths. However, they are situated for general coverage of the upper part of the saturated zone, through which ground-water flow paths from the repository are likely.

The construction of the geologic and hydrologic series of test holes was such that the first early measurements of head were composites, reflecting averages of all the members of the Paintbrush and Crater Flat Tuffs that were penetrated below the water table. Subsequent to initial completion, four piezometers of varying lengths were installed in one drillhole (drillhole USW H-1) in order to measure heads in each of four zones (water levels for the upper three intervals are very similar; water level in the deepest interval is about 54 m higher; refer to Table 3-24 and Robison, 1986). A single semipermanent packer was installed between permeable zones in each of 5 hydrologic holes (drillholes UE-25b#1, USW H-3, USW H-4, USW H-5, and USW H-6), enabling comparison of head in the zones above and below the depth of the packer setting. Potentiometric heads in the Tertiary rocks penetrated in drillhole UE-25p#1 were measured while drilling, but these rocks were sealed off before the well penetrated the underlying Paleozoic rocks, and present measurements reflect head only of the Paleozoic interval (Section 3.9.1.2).

Because the range of water-level altitudes on the eastern side of Yucca Mountain area is small, measurement precision is important for determination of fluctuations, gradients, and probable flow paths. Therefore, a discussion of some of the aspects of water-level measurements is presented below.

Periodic measurements of water levels typically involve lowering, over a pulley with depth counter, a portable cable to which is attached a float switch or pressure transducer with readout to land surface; depth adjustments include a factor for counter error, and conversion is made from transducer output (millivolts) to submergence of the transducer meters or feet. Repeat measurements are made on the same date, and averaged. Because the depths to water are large, probable error for an individual water-level measurement may be as much as 0.1 m.

Table 3-23. Completion records of unsaturated zone boreholes (page 1 of 2)

Borehole designation[a]	Drilling method	Total depth (m)	Diameter (cm)	Depth interval (m)	Casing inside diameter (cm)	Casing depth interval (m)	Rock-stratigraphic unit penetrated at total depth
USW UZ-1	Reverse vacuum	386.8	122 91 61 44.5	0-12.5 12.5-29.6 29.6-30.8 30.8-386.8	41	0-12.0	Topopah Spring Member (Paintbrush Tuff)
UE-25UZ-4	Odex/ cored	111.9	15 10.8	0-68.9 68.9-111.9	13	0-17.7	Topopah Spring Member (Paintbrush Tuff)
UE-25UZ-5	Odex	111.3	15	0-111.3	13	0-5.2	Topopah Spring Member (Paintbrush Tuff)
USW UZ-6	Reverse vacuum	575.2	76 61 44	0-12.2 12.2-103.9 103.9-575.2	66 48	0-12.2 0-98.8	Prow Pass Member (Crater Flat Tuff)
USW UZ-6S	Odex	158.2	22 18	0-150.9 150.9-158.2	10	0-0.91	Topopah Spring Member (Paintbrush Tuff)
USW UZ-7	Odex	63	15.2	0-63	12.7	0-6	Topopah Spring Member (Paintbrush Tuff)

Table 3-23. Completion records of unsaturated zone boreholes (page 2 of 2)

Borehole designation[a]	Drilling method	Total depth (m)	Diameter (cm)	Depth interval (m)	Casing inside diameter (cm)	Casing depth interval (m)	Rock-stratigraphic unit penetrated at total depth
USW UZ-8	Odex	107	21.6	(b)			Topopah Spring Member (Paintbrush Tuff)
USW UZ-13	Odex/ cored	131	15.2 10	0-125 125-131	12.7	0-101	Topopah Spring Member (Paintbrush Tuff)

[a]Location of boreholes shown on Figure 3-27.
[b]Drilling incomplete.

Table 3-24. Ground-water levels, Yucca Mountain area[a] (page 1 of 3)

Hole or well number	Location[b] North (ft)	Location[b] East (ft)	Hole depth[c] (m)	Land-surface altitude[d] (m)	Depth correction[e] (m)	Date measured[f]	Geologic unit[g]	Water level (corrected) Interval[h] (m)	Water level (corrected) Depth to water[i] (m)	Water level (corrected) Altitude[j] (m)
UE-25b#1	765,243	566,416	1,220	1,200.7	0.25	12/03/83	Th/Tlr	Composite	470.6	730.9
						08/01/83	Th/Tct	471-1199	470.3	730.4
						08/01/83	Tct/Tlr	1199-1220	472.2	728.5
UE-25c#1	757,095	569,680	914	1,130.6	0.06	11/07/83	Tpt/Tct	Composite	400.3	730.3
UE-25p#1	756,171	571,485	1,805	1,114.2	0.06	02/ /83	Th/Tcp	383-500	383.9	730.1
						11/07/83	Pz/Pz	1297-1805	364.7	749.4
USW G-1	770,500	561,000	1,829	1,325.9	0.67	03/23/82	Tcp/Tof	Composite	571.7	754.2
USW G-2	778,824	560,504	1,831	1,553.9	0.16	09/17/82	Tpt/Tof	Composite	524.9	1,029.0
USW G-3	752,780	558,483	1,533	1,480.5	0.57	11/30/83	Tcb/Tof	Composite	750.3	730.2
USW G-4	765,807	563,082	915	1,269.5	1.53	04/27/83	Tcp/Tct	Composite	539.5	730.0
USW H-1	770,254	562,388	1,829	1,303.0	0.19	02/25/82	Tcp/Tof	Composite	572.1	730.9
						11/01/83	Tcp/Tcp	572-673	572.4	730.7
						11/01/83	Tcb/Tcb	716-765	572.4	730.7
						11/01/83	Tct/Tct	1097-1123	571.7	731.4
						11/01/83	Tof/Tof	1783-1814	518.2	784.9
USW H-3	756,542	558,452	1,219	1,483.2	0.08	11/19/82	Tcb/Tlr	Composite	570.8	732.4
						11/03/83	Tcb/Tlr	751-1190	750.8	732.3
						11/03/83	Tlr/Tlr	1190-1219	729.0	754.0
USW H-4	761,643	563,911	1,219	1,248.5	0.45	12/30/82	Tcp/Tlr	Composite	518.7	729.8
						06/16/83	Tcp/Tlr	518-1181	518.2	730.3
						06/16/83	Tlr/Tlr	1181-1219	518.1	730.4
USW H-5	766,634	558,909	1,219	1,478.9	0.08	12/22/83	Tcb/Tl	Composite	704.2	774.7
						11/07/83	Tcb/Tl	704-1091	703.8	775.1
						11/07/83	Tl/Tl	1091-1219	703.8	775.1
USW H-6	763,299	554,075	1,220	1,301.7	0.05	12/15/82	Tcp/Tlr	Composite	526.6	775.1
						10/24/83	Tcp/Tcb	526-1187	526.1	775.6
						10/24/83	Tct/Tlr	1187-1220	524.7	777.0
USW WT#1	753,941	563,739	515	1,201.4	0.33	10/31/83	Th/Tcb	Composite	471.0	730.4
USW WT#2	760,661	561,924	628	1,301.3	0.53	11/01/83	Tcp/Tcp	Composite	571.0	730.3

Table 3-24. Ground-water levels, Yucca Mountain area[a] (page 2 of 3)

Hole or well number	Location[b] North (ft)	Location[b] East (ft)	Hole depth[c] (m)	Land-surface altitude[d] (m)	Depth correction[e] (m)	Date measured[f]	Geologic unit[g]	Water level (corrected) Interval[h] (m)	Water level (corrected) Depth to water[i] (m)	Water level (corrected) Altitude[j] (m)
UE-25 WT#3	745,995	573,384	348	1,030.0	0.27	10/31/83	Tcb/Tcb	Composite	300.5	729.5
UE-25 WT#4	768,512	568,040	482	1,169.2	0.46	11/01/83	Th/Th	Composite	438.9	730.4
UE-25 WT#6	780,576	567,524	383	1,314.8	0.24	10/31/83	Th/Th	Composite	283.8	1,031.3
USW WT#7	755,570	553,891	491	1,196.9	0.03	10/24/83	Tpt/Tcp	Composite	421.2	775.7
USW WT#10	748,771	553,302	430	1,123.4	0.03	10/24/83	Tpt/Tpt	Composite	347.7	775.7
USW WT#11	739,070	558,377	441	1,094.1	0.12	10/24/83	Tpt/Th	Composite	363.9	730.2
UE-25 WT#12	739,726	567,011	399	1,074.7	0.20	10/31/83	Tpt/Th	Composite	345.4	729.3
UE-25 WT#13	756,884	578,843	352	1,032.5	0.01	10/31/83	Tpt/Tpt	Composite	303.3	729.2
UE-25 WT#14	761,651	575,210	399	1,076.4	0.09	11/07/83	Tpt/Th	Composite	346.2	730.2
UE-25 WT#15	766,116	579,806	415	1,083.2	0.19	12/01/83	Tpt/Tpt	Composite	354.2	729.0
UE-25 WT#16	774,420	570,395	519	1,210.9	0.06	12/01/83	Th/Th	Composite	472.7	738.2
UE-25 WT#17	748,420	566,212	443	1,124.0	0.48	11/07/83	Tcp/Tcp	Composite	394.6	729.6
Well J-11	740,968	611,764	405	1,050.0	--[k]	03/22/73	--/Tpt	Composite	317.4	732.6
Well J-12	733,509	581,011	347	953.5	--	12/05/83	Tpt/Tpt	Composite	226.2	727.3
Well J-13	749,209	579,651	1,063	1,011.3	--	10/31/83	Tpt/Tlr	Composite	283.2	728.1
USW VH-1	743;356	533,626	762	963.5	--	02/12/81	Qa/Tcb	Composite	184.2	779.3
USW VH-2	748,320	526,264	1,219	974.4	--	04/23/83	Qa/Tcb	Composite	164.0	810.4

[a]Robison (1986). See text for discussion of methods.
[b]Location: Nevada State Coordinate System Control Zone.
[c]Hole depth: Total depth drilled.
[d]Land-surface altitude: Altitude above sea level at well, as determined by U.S. Geological Survey National Mapping Division, 1984. Altitude at wells J-11, J-12, J-13 and holes USW VH-1, USW VH-2 reported by Holmes and Narver, Inc., contractor to U.S. Department of Energy.
[e]Depth correction: Correction needed to adjust measured depth or altitude to true value because of hole deviation from vertical. The correction is computed for a depth approximately equal to the depth of the measured water level; this correction is obtained from a downhole gyroscopic survey.

Footnotes (continued)

[f]Date measured: Date of a water-level measurement.

[g]Geologic unit: Unit before the virgule is the shallowest geologic unit represented by the water level; unit after virgule is the deepest geologic unit represented by the water level. Units are defined as follows: Qa = alluvium; Tpt = Topopah Spring Member of Paintbrush Tuff; Th = tuffaceous beds of Calico Hills; Tcp = Prow Pass Member of Crater Flat Tuff; Tcb = Bullfrog Member of Crater Flat Tuff; Tct = Tram Member of Crater Flat Tuff; Tl = Lava; Tlr = Lithic Ridge Tuff; Tof = older flows and tuffs; Pz = Paleozoic rocks.

[h]Interval: Depth interval of the hole represented by the water-level measurement. Composite levels represent mixed hydraulic heads of the entire interval between the water table or the lower end of the casing and the bottom of the hole. Where a specific interval is indicated, the zone was isolated using a single packer installed to determine hydraulic head differences above and below the packer.

[i]Depth to water: Depth based on direct measurement of water levels using downhole wireline equipment, adjusted for depth correction, where available. Accuracy of measurements is approximately ± 0.1 m. Depth in USW VH-2 estimated from geophysical logs.

[j]Altitude: Computed altitude of water level above sea level, based on land surface altitude and measured depth to water (corrected). Where more than one altitude is reported, the value used on the map (Figure 3-28) is underscored in the table.

[k]-- indicates no data.

The apparent range of water-level fluctuations, as indicated by recently-installed downhole pressure transducers in some drillholes, is commonly smaller than the precision from periodic or repetitive measurements made with calibrated tapes or cables, and, therefore, hydrographs of the limited data available might be imprecise and possibly misleading. For some uses a need exists for more accurate and precise measurement of water-level changes than normally has been feasible for deep water levels; the problem is discussed further in the following paragraph and will be addressed in the continuing monitoring program (Section 8.3.1.2.3).

Pressure transducers can sense extremely small changes of water levels, but they require determination of a factor to convert transducer output (millivolts) to depth (meters) of submergence of the transducer below the water level. This factor may change slightly, and it must be determined both before and following the period of transducer measurements, using measurements independent of the transducer. In addition, and perhaps more important, some transducers have exhibited zero-point (zero submergence) drifts equivalent to a meter or more of water-level change. Therefore, apparent trends in water levels (beyond the earth-tide or other cyclic variations that occur within a few days or less) cannot be confirmed until the downhole measuring equipment is removed, checked, and recalibrated; and until prorated, adjusted values of the data have been computed and plotted for the period between calibrations. This process will be part of the continuing monitoring program, as described in Section 8.3.1.2.3.

Ground-water flow direction and travel time are, in part, a function of hydraulic gradient, which is determined from water levels in wells. At Yucca Mountain, high accuracy and precision are needed because in parts of the area (Figure 3-28) the water table is nearly flat and calculation of the gradient is sensitive to small errors in water-level measurements. For comparison of levels among wells, true depths must be calculated, which involves a correction for hole deviation from vertical. To calculate water-level altitudes, highly precise altitudes of the measuring points at land surface are needed.

A further complicating factor that may affect the water levels measured in the saturated zone relates to density effects. However, effects on water levels caused by water-density differences due to differences in ground-water temperatures among wells probably are small. In addition, since the water in most of the wells in the eastern and southeastern areas of Yucca Mountain have similar chemistries and temperatures, density differences probably have little if any effect on the hydraulic gradient within that area.

3.9.1.2 Potentiometric levels

This section provides data on matric potentials obtained from drillhole USW UZ-1 in the unsaturated zone. In addition, data on potentiometric levels from wells in the saturated zone are presented and discussed, as well as an assessment of the possibility of short-term changes in these levels.

3.9.1.2.1 Unsaturated zone

In situ measurements of matric potential within the unsaturated zone at Yucca Mountain have been attempted only at the 33 instrumentation stations that are arrayed vertically within the prototype monitoring borehole USW UZ-1. A preliminary analysis and interpretation of data collected in drillhole usw uz-1 over a 2-yr period following completion of the borehole are presented by Montazer et al. (1985). As described in Section 3.9.1.1.1, matric potentials in the borehole are being measured both by heat-dissipation probes and by thermocouple psychrometers. Profiles of matric potential within the borehole on a sequence of selected dates are shown in Figure 3-30 for the measurements made by heat-dissipation probes, and in Figure 3-31 for the thermocouple-psychrometer data (Montazer et al., 1985). Much of the data shown in Figure 3-31 exceed the useful range of matric potential over which the heat-dissipation probes were calibrated (-0.01 to -0.5 MPa). Some of the higher matric-potential data shown in Figure 3-30 exceed the maximum value, -0.5 MPa for which the thermocouple psychrometers can be calibrated reliably. Nonetheless, the data are useful to indicate the trends. The measurements of matric potential at each level within the borehole exhibited a trend during which, following the disturbance of natural conditions produced by drilling and instrumenting the borehole, the immediate environment of each instrument presumably equilibrated with the ambient hydrologic conditions within the surrounding host rock. In addition, because the heat-dissipation probes and the thermocouple psychrometers were emplaced under differing initial conditions in different backfill materials of different hydrologic properties, there is a considerable range of values of matric potential measured simultaneously by different instruments at the same level within the borehole. By May 1985, however, most of the instruments appeared to have stabilized sufficiently to yield a matric-potential profile that probably is indicative of ambient conditions within the host rock (Montazer et al., 1985).

Presuming conditions within the borehole to have equilibrated with those in the host rock, the data of Figures 3-30 and 3-31 indicate that matric potentials within the PTn hydrogeologic unit at drillhole USW UZ-1 range from -10 to -1 bars (-1 to -0.1 MPa) with a mean value of about -5 bars (-0.5 MPa) over the thickness of the unit. The matric potentials within the TSw unit range from -10 to -1 bars (-1.0 to -0.1 MPa), with an approximately constant mean value of about -3 bars (-0.3 MPa) over the thickness of the unit. Montazer et al. (1985) concluded that downward moisture flux within the TSw unit occurs predominantly as liquid-water flow within the rock matrix of the unit, with little or no liquid-water flow within the fractures. Assuming that the nearly constant matric potential over the depth interval from 122 to 224 m in drillhole drillhole USW UZ-1 (Figure 3-31) implied unit vertical hydraulic gradient, Montazer et al. (1985) estimated that the downward liquid-water flux within the TSw unit at drillhole USW UZ-1 probably is within the range from 0.1 to 0.5 mm/yr.

Pneumatic potentials (pore-gas pressures) are being monitored by downhole pressure transducers emplaced in borehole USW UZ-1 and have been measured within a piezometer nest installed in borehole UE-25a#4, about 1.6 km southeast of drillhole USW UZ-1. Diurnal and barometrically induced fluctuations of gas pressure of about 0.25 kPa (Montazer et al., 1985) have been observed in these boreholes to depths of about 30 m. Such fluctuations are apparently damped out below this depth, although seasonally induced

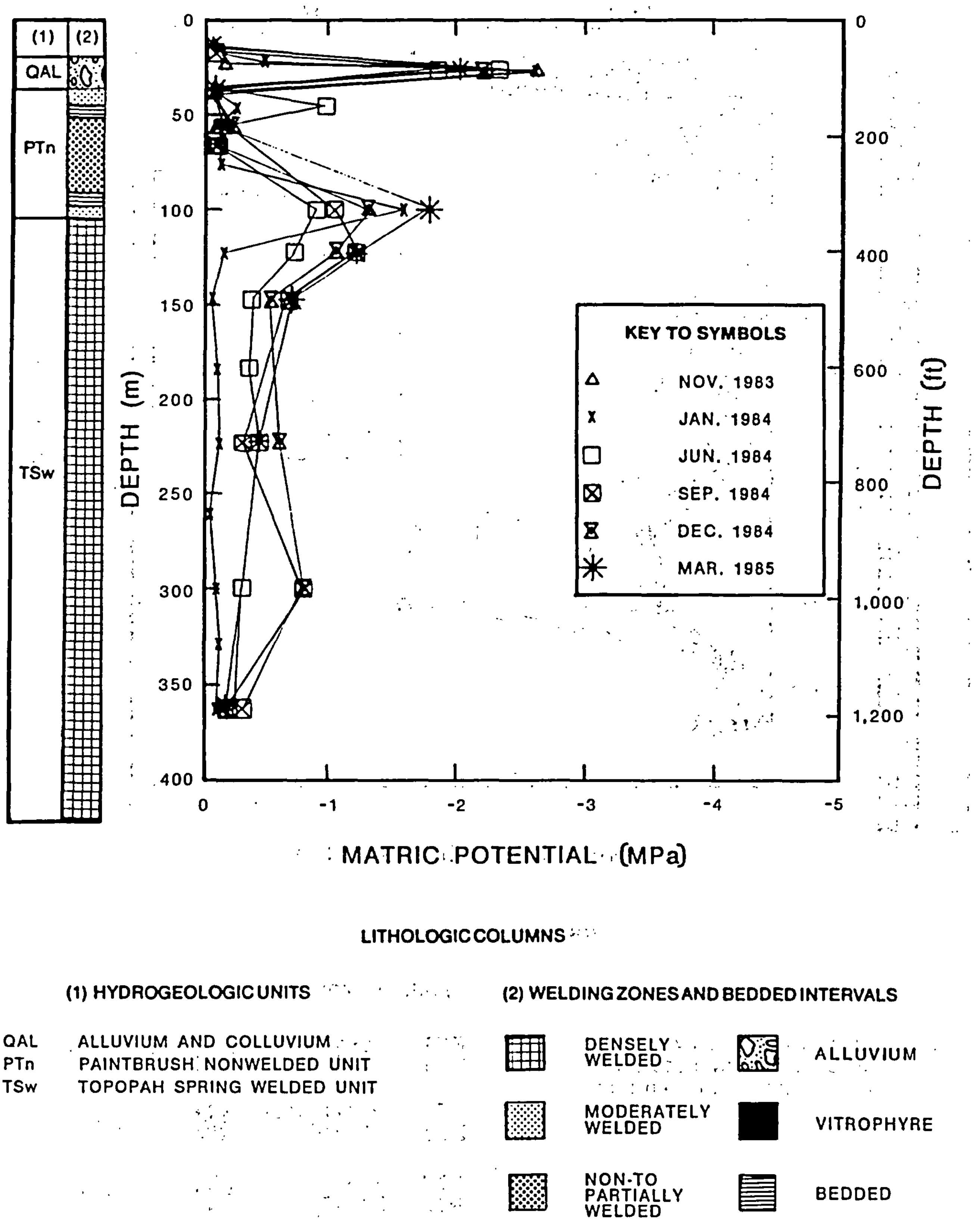


Figure 3-30. Matric-potential profiles for selected dates at monitoring borehole USW UZ-1 based on data from heat-dissipation probes. Modified from Montazer et al. (1985).

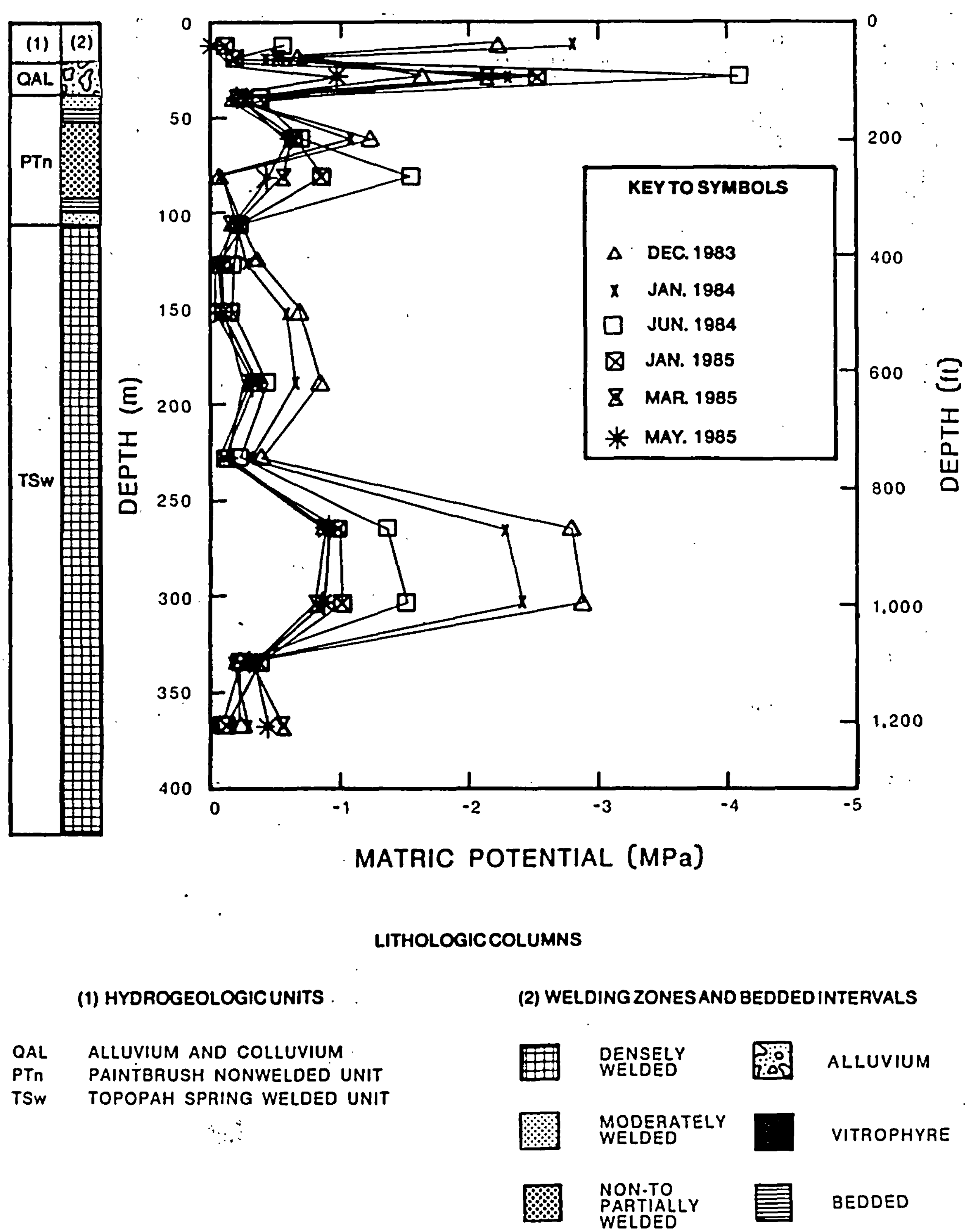


Figure 3-31. Matric-potential profiles for selected dates at monitoring borehole USW UZ-1 based on data from thermocouple psychrometers. Modified from Montazer et al. (1985).

pressure variations are observed to occur at greater depths (Montazer et al., 1985). The pneumatic data were used by Montazer et al. (1985) to make preliminary estimates of air permeability in the uppermost units penetrated by these boreholes but have not been interpreted in terms of the overall bulk-gas flow system within the unsaturated zone.

3.9.1.2.2 Saturated zone

The present monitoring program consists of measuring water levels and observing their variations with time. Selected water levels in the vicinity of Yucca Mountain are shown in Figure 3-28 and Table 3-24. The figure and table are modified from Robison (1986), the most recent source of published data; however, the figure and table contain revisions based on resurveying in 1984 of land-surface altitudes at most of the well sites. The water levels range in altitude from about 1,030 to 730 m above sea level and generally represent water-table or unconfined conditions. Within the level of available precision, potentiometric levels show little variation with depth in the upper part of the saturated zone (Table 3-24). In the deeper part of the saturated zone (drillhole USW H-1, in the older Tertiary rocks; drillhole UE-25p#1, in the Paleozoic carbonate rocks), potentiometric heads are higher than in the overlying rocks (Table 3-24).

Figure 3-25 a simplified section through Yucca Mountain (location shown on Figure 3-28, shows the general relationship of stratigraphic units and the water table. For clarity, only the Solitario Canyon fault is shown, although the section is known to include numerous steeply dipping normal faults.

In the Yucca Mountain area, the potentiometric surface occurs principally in members of the Paintbrush Tuff and underlying Crater Flat Tuff (the geologic units, not the hydrostratigraphic units defined for the unsaturated hydrologic zone). Slope of the potentiometric surface at Yucca Mountain, based on gradients indicated by the contours, is south to southeast, similar to the regional topographic slope.

The gradient in the north is relatively steep compared with that in the south. Water-level altitudes in Figure 3-28 are highest to the north at drillholes USW G-2 and UE-25 WT#6; however, it is not known whether the southward slope toward drillhole USW H-1 is uniform, or if there are abrupt flections. The cause for this steep slope is not known yet; it may be that southward movement of ground water is inhibited in this area by a low-permeability formation, such as the tuffaceous beds of Calico Hills, or by a fault or other unknown structural control. Test drilling to resolve these, and possible alternate, hypotheses is planned (Section 8.3.1.2.3).

West of the crest of Yucca Mountain, in drillholes USW H-6, USW WT-7, and USW WT-10 and also in USW H-5 on the crest, the water levels are about 775 m above sea level. Water levels are as much as 45 m lower at drillholes USW G-3 and USW H-3, just east of drillhole USW WT-7. A fault in Solitario Canyon may itself be poorly permeable and restrict eastward movement of ground water, or the fault may juxtapose permeable zones against less permeable zones and thereby restrict movement. Pumping tests in existing or proposed drillholes are expected to be used to determine the hydraulic effects of the fault (Section 8.3.1.2.3.1).

From the eastern edge and southern end of Yucca Mountain to western Jackass Flats, the potentiometric surface ranges from about 728 to 730 m in altitude with a general southeastward slope (Figure 3-28, and Robison, 1986).

Hydrographs of water-level data are not presented, for the reasons given in Section 3.9.1.1.2. In regions where precipitation is greater and water levels are shallower, there is typically a well-defined seasonal or annual correlation between precipitation and ground-water levels. At Yucca Mountain, however, ground-water levels are not expected to show short-term or seasonal fluctuations that can be correlated with precipitation. This is because of extremely low rates of net infiltration and recharge attributable to local precipitation, the great depths to the water table, and ground-water travel times through the unsaturated zone that may be many thousands of years. Long-term precipitation data are not available for the site, although precipitation stations have been established recently in the Yucca Mountain area as part of a study to determine rainfall-infiltration relationships (Section 8.3.1.2.1).

Well J-13, 8 km from the site, and well J-12, 12 km from the site, (Figure 3-22) are in service for water supply; their production is discussed in Section 3.9.7.

3.9.1.3 Hydrochemistry

This section presents the hydrochemical information obtained from the baseline monitoring program of the site and its immediate surroundings. Hydrochemical data have not been collected at the site long enough for reliable time series to be developed. Therefore, temporal trends, if they exist, cannot be directly identified from the available data at this time. Some indirect information about changes in the hydrochemical conditions at the site over time can be obtained from understanding the hydrochemical evolution of the waters interacting with their host-rock environment. Their interaction is discussed in detail in Sections 4.1.1.4, 4.1.2.9, and 4.4.2. On the basis of this discussion, there is no reason to believe that while the existing climatic conditions prevail, the natural hydrochemical conditions at the site will not remain very similar to those currently observed.

Chapter 4 presents in detail the current knowledge of site ground-water temperature (4.1.2.8), major chemical composition (4.1.2.2), dissolved gas concentrations (4.1.2.5), pH and Eh (Tables 4-6 and 4-7 respectively), background radioactivity (4.1.2.6) and organic content (4.1.2.4), which will not be repeated here.

Major-ion data are available from six wells on, or immediately adjacent to the site. These wells tap the tuff formations. The data have been plotted on Stiff diagrams in Figure 3-32, which show that sodium bicarbonate water prevails throughout the area. This is consistent with the regional predominance of that facies as seen in the Piper diagram in Figure 3-12.

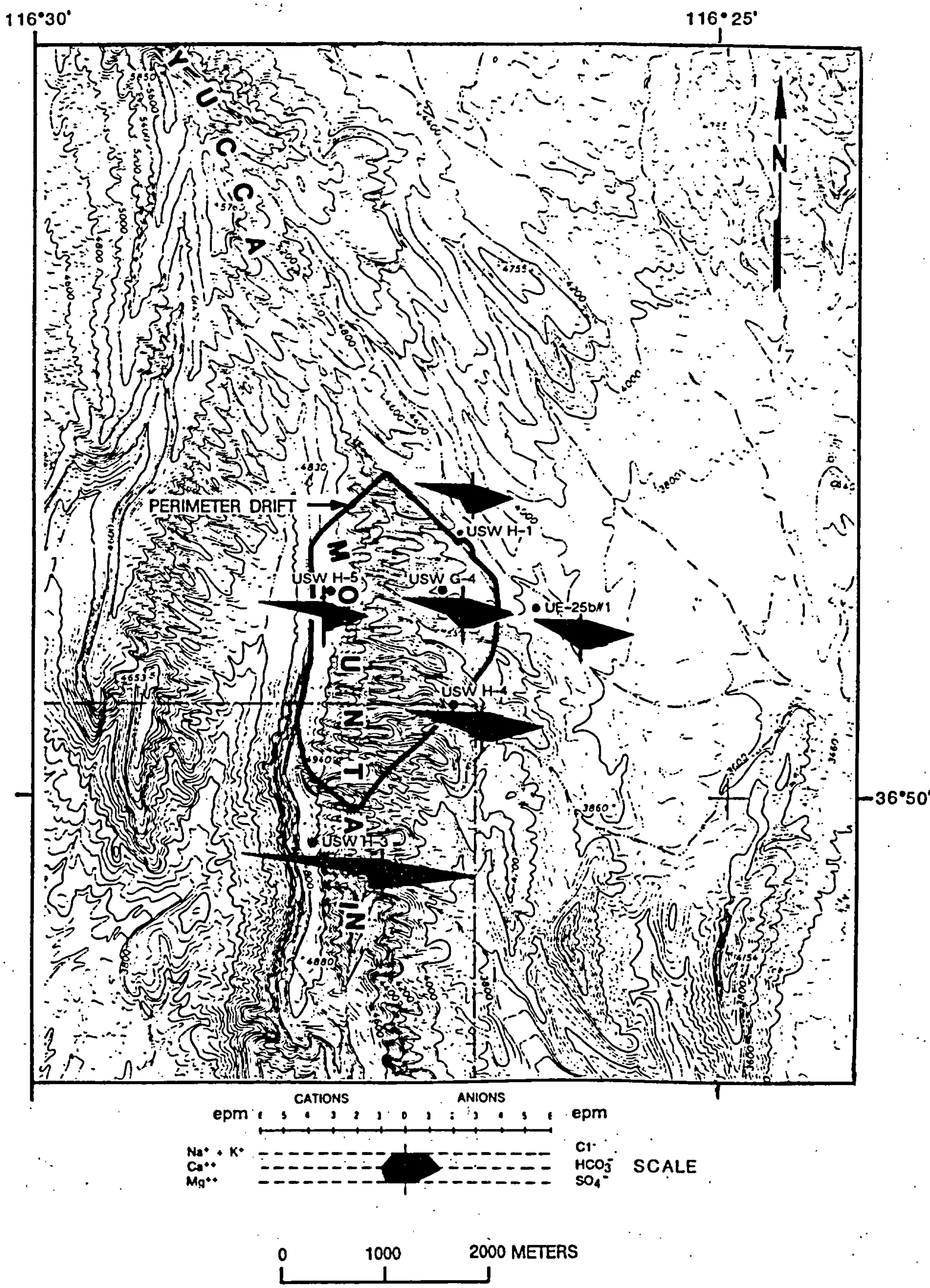


Figure 3-32. Geochemical facies in the tuff formation in the immediate area around Yucca Mountain, with Stiff diagrams indicating the composition of six samples

Total dissolved solids and specific conductance are parameters measured to get a general idea of the salinity of a sample when complete analyses are not available. The total dissolved solids average about 300 mg/L and specific conductance is approximately 300 microsiemens/cm (at 25°C) for the ground water at the site. These parameters are not presented in detail since they contribute little when complete chemical analyses are available such as those in Tables 4-6 and 4-7 of Chapter 4. No density measurements of the local ground water are available; but because of the low solute concentration, values should vary insignificantly from 1 g/cm^3 (at 4°C).

Environmental isotopic data are available for ground-water samples from wells in the tuff aquifers beneath Yucca Mountain (Benson et al., 1983; Benson and McKinley, 1985). Both carbon-14 activity and "uncorrected, apparent radiocarbon age" of the samples were reported. In areas where carbonate minerals may contribute significant amounts of carbon, it can be misleading to use these apparent ages in interpreting a flow system. Such apparent ages, which can be off by more than a factor of two, have been omitted in Table 3-25. Since corrected ages (determined by modeling the initial radiocarbon activity of the water; e.g., IAEA, 1983) are not available, only the sample activity measurements were used. The measured carbon-14 activities are relatively homogeneous for an area this size, particularly when accounting for sampling, sample preparation, and analytical uncertainties. Samples from the two southernmost drillholes (USW H-3 and USW H-4) have lower carbon-14 content (mean value 11.1 percent modern carbon) than samples from the other, more northerly drillholes (mean value 20.1 percent modern carbon) (Table 3-25). The significance of this difference cannot be fully assessed without carbon-14 modeling. Nevertheless, ground-water residence times of the southern samples may be on the order of 5,000 yr greater than the northern samples. Because significant amounts of carbonate minerals do not occur in the tuff or in tuffaceous valley fill with which these ground waters have come into contact, minimal radiocarbon dilution may have occurred from such contact and apparent ages may be more realistic than at other sites.

The δ carbon-13 ($\delta^{13}C$) values may show a spatial variability similar to those of the carbon-14. The values are consistent with recharge under very poorly vegetated conditions. The $\delta^{13}C$ value reported for sample USW H-3 is above the mean atmospheric value for carbon dioxide. The explanation of this unusual phenomenon could shed light on the differences in radiocarbon content between this sample and the northern ones. The $\delta^{13}C$ values below about -10 parts per thousand in dilute waters suggest that little carbonate rock/water and soil gas/water exchange has occurred (Section 3.7.3).

The three tritium values of <62 TU in Table 3-25 serve only to indicate that no large amounts of bomb-test tritium have reached the aquifer at those points. The other samples, which were analyzed by a more sensitive method to give a more precise result, are consistent with trace tritium contamination of samples of very old water (very old, in the context of tritium dating implies several hundred years or more). Such contamination is common and not unexpected at Yucca Mountain.

The deuterium and oxygen-18 data in Table 3-25 plot on and below the meteoric line (Section 3.9.1.3), occurring between a deuterium excess of +10 (mean continental meteoric water) to +5. Such a small deviation from the

Table 3-25. Environmental isotope data for ground-water samples from the tuff aquifers under the exploratory block and its immediate area[a]

Well designation[b]	Collection date	δD (o/oo SMOW)[c]	$\delta^{18}O$ (o/oo SMOW)[c]	$\delta^{13}C$ (o/oo PDB)[d]	^{14}C (pmc)[e]	HTO (TU)[f]
UE-25b#1	08/07/81	-99.5	-13.4	-10.7	--[g]	--
UE-25b#1	09/09/81	-101.0	-13.4	-10.7	16.7	<62.0
UE-25b#1	07/20/82	-99.5	-13.5	-8.6	18.9	0.6
USW G-4	12/09/82	-103.0	-13.8	-9.1	22.0	--
USW H-1	10/20/80	-103.0	-13.4	--	19.9	<6.0
USW H-1	12/08/80	-101.0	-13.5	-11.4	23.9	<6.0
USW H-3	03/14/84	-101.0	-13.9	-4.9	10.5	0.6
USW H-4	05/17/82	-104.0	-14.0	-7.4	11.8	<3.0
USW H-5	07/03/82	-102.0	-13.6	-10.3	18.2	<62.0
USW H-5	07/26/82	-102.0	-13.6	-10.3	21.4	<62.0

[a]Source: Benson and McKinley (1985).
[b]Well locations indicated in Figure 3-32.
[c]δD and $\delta^{18}O$ are reported in parts per thousand relative to Standard Mean Ocean Water (SMOW) standard.
[d]$\delta^{13}C$ is reported in parts per thousand relative to Peedee belemnite carbonate (PDB) standard.
[e]^{14}C activity is reported as a percent of the modern carbon (pmc) standard.
[f]T is reported in tritium units (TU).
[g]-- indicates no data.

world-wide average meteoric deuterium excess is within expected local continental variation. The water is extremely depleted in heavy isotopes of both oxygen and hydrogen, consistent with high altitude, cold (winter) continental recharge or snow-melt. No evaporative enrichment or thermal alteration is observed. No complete hydrochemical or isotopic analyses are available for water from the unsaturated zone at the site. Methods (triaxial compression, high-speed centrifuge and vacuum distillation) are currently under development for extracting uncontaminated samples upon which to perform these analyses. Yang (1986) has reported some preliminary calcium and sodium concentration data, showing that calcium is elevated in the pore water relative to the ground water, to the extent that it dominates over sodium. Complete chemical and isotopic characterization of the infiltrating pore water is needed (1) to develop an understanding of the hydrochemical nature of the water that may contact a waste package and (2) to isotopically trace the movement of these waters through the unsaturated zone. The plans for collecting these data as a function of depth are presented in Section 8.3.1.2.3.

The carbon-14 and carbon-13 composition of the unsaturated zone CO_2(g) phase has been determined by Yang et al. (1985a) on samples obtained by the new methods developed by Haas et al. (1983). Radiocarbon from bomb-test fallout was observed to a depth of 12.2 m in borehole UZ-1 on the exploration block. Radiocarbon activity decreased to below 100 percent modern carbon below 18.3 m, which may indicate that downward gas-phase transport from the surface has not occurred beyond this depth since the mid-1960. Improvements in sample collection methods and the interpretation of these results with pore-water hydrochemical data as outlined in Section 8.3.1.2.3 will enhance the understanding of two-phase transport in the unsaturated zone at the site.

3.9.2 HYDRAULIC CHARACTERISTICS

This section presents information on the hydraulic characteristics of the unsaturated and the saturated zones. The hydraulic characteristics of the unsaturated zone include fracture characteristics, porosity, saturated matrix hydraulic conductivity, and moisture characteristic relations. For the saturated zone, values for hydraulic conductivity, transmissivity, porosity, and storage coefficient are presented and discussed.

3.9.2.1 Hydraulic characteristics of the unsaturated zone

Mean values of hydrologic properties for most of the hydrogeologic units defined in Table 3-22 are presented in Table 3-26. The compilation of Montazer and Wilson (1984) included data from several sources. The data of Peters et al. (1984) were based on analyses of core samples from test wells USW G-1, USW G-4, and USW GU-3; the data of Tien et al. (1985) includes data from wells USW H-1, USW G-1, J-13, UE-25a#1, and USW GU-3; and the data reported by Weeks and Wilson (1984) were obtained from core samples from well USW H-1. The range of mean values among the references cited for each property within each hydrogeologic unit reflects the effects of lateral and vertical spatial heterogeneity within each unit. Table 3-26 provides only

Table 3-26. Summary of compilations of hydrogeologic properties of hydrogeologic units within the unsaturated zone, Yucca Mountain

Hydrogeologic unit[a]	Source of data	Range of thickness (m)	Grain density (kg/m³)[b]	Fracture density (no./m³)[c]	Porosity[b]	Saturated matrix hydraulic conductivity (m/s)
TCw	(d)	0-150	ND[f]	10-20	0.12	2×10^{-11}
	(e)	ND	2,490	ND	0.08	9.7×10^{-12}
PTn	(d)	20-100	ND	1	0.46	1×10^{-7}
	(e)	ND	2,350	ND	0.40	3.9×10^{-7}
TSw	(d)	290-360	ND	8-40	0.14	3.5×10^{-11}
	(e)	ND	2,580	ND	0.11	1.9×10^{-11}
CHnv	(d)	100-400	ND	2-3	0.37	5×10^{-8}
	(e)	ND	2,370	ND	0.46	2.7×10^{-7}
CHnz	(d)	100-400	ND	2-3	0.31	9×10^{-11}
	(e)	ND	2,230	ND	0.28	2.0×10^{-11}

[a]Hydrogeologic units are defined on Table 3-22.
[b]See Chapter 2 for more data.
[c]Scott et al. (1983).
[d]Montazer and Wilson (1984).
[e]Peters et al. (1984) and Peters et al. (1986).
[f]ND = no data.

values typical of the samples tested for hydrologic properties. These data are based, in general, on too few samples (several score for the entire unsaturated zone at Yucca Mountain) to permit meaningful statistical analyses to be performed for each hydrogeologic unit. An indication of the variance within and between sample sets is shown by the saturated matrix hydraulic conductivity, whose values listed in Table 3-26 range over two orders of magnitude.

The discrepancy in the values reported in Table 3-26 for saturated matrix hydraulic conductivity for hydrogeologic unit CHnv reflects, in part, the current uncertainty in the position of hydrogeologic unit contacts and, in part, the heterogeneity of the units. Rock-sample collection for the measurement of hydrologic properties is to be done through the program of surface-based borehole drilling and coring and of sampling within the exploratory shaft, as described in Section 8.3.1.4. Plans to define the hydrogeologic framework are described in Section 8.3.1.2.

The hydrologic property data of Table 3-26 must be supplemented by developing sets of moisture-characteristic curves, that is the functional dependence of liquid-water saturation and relative hydraulic conductivity on the liquid-water potential within the rock matrix and fractures appropriate for each hydrogeologic unit. In unfractured rocks, these relations refer to the storage and movement of liquid water within and through the interstitial pore space. In fractured rocks, allowance must be made for the storage and movement of water within the interconnected fracture openings as well as for the movement of water between the fracture openings and the rock-matrix pore space. Standard mercury-intrusion (Gregg and Sing, 1967), centrifugal (Russell and Richards, 1938; Hassler and Brunner, 1945), pressure plate (Hillel, 1980) and psychrometric (Papendick and Campbell, 1981) techniques are available for the laboratory determination of the relation between matric potential and saturation in soil and unfractured rock samples. Saturated hydraulic conductivities are measured using standard permeametry techniques (Hillel, 1980). The saturated matrix hydraulic conductivity measurements reported in Table 3-26 were generally made using a constant-head permeametry technique on samples from drillhole core.

Techniques for the measurement of relative hydraulic conductivity values are available (Amyx et al., 1960) but are generally limited in applicability to consolidated rocks with permeabilities much larger than the values for welded tuff or zeolitic tuff samples. Techniques for the measurement of relative hydraulic conductivity on very low permeability tuffs, such as welded tuff matrix material from TSw, are under development, and theoretically based methods have been formulated to estimate relative hydraulic conductivity in unconsolidated porous media from matric potential, saturation, and pore-size-distribution data (Brooks and Corey, 1964; Mualem, 1976).

A set of moisture-retention curves under drainage conditions relating matric-potential and saturation is shown in Figure 3-33 and was developed by Peters et al. (1984) for the matrix properties of most of the hydrogeologic units listed in Table 3-22. These curves were obtained by fitting the van Genuchten (1978) analytic representation to laboratory psychrometric data obtained for unfractured samples extracted from cores from test wells USW G-4 and USW GU-3. Because psychrometric techniques are appropriate only for matric potentials less than about -3 bars (-0.3 MPa), the moisture-retention curves reported by Peters et al. (1984) are not well determined for matric potentials that exceed this value. In lieu of direct measurements, the van Genuchten (1978) representation can also be used to estimate matrix relative hydraulic conductivity for these units. Such estimates must be regarded as highly tentative, however, because it is not known to what extent this analytic representation for relative hydraulic conductivity is appropriate for the tuffs at Yucca Mountain (Section 8.3.1.2.2). Furthermore, the curves in Figure 3-33 are based on laboratory determinations on small sample sets from only two locations, and therefore, the curves may not be representative of the units at Yucca Mountain as a whole.

Standard laboratory methods are not yet available by which to determine the moisture-characteristic relations for fractures and fractured rocks, and reliance must be made on theoretically based models and approximations.

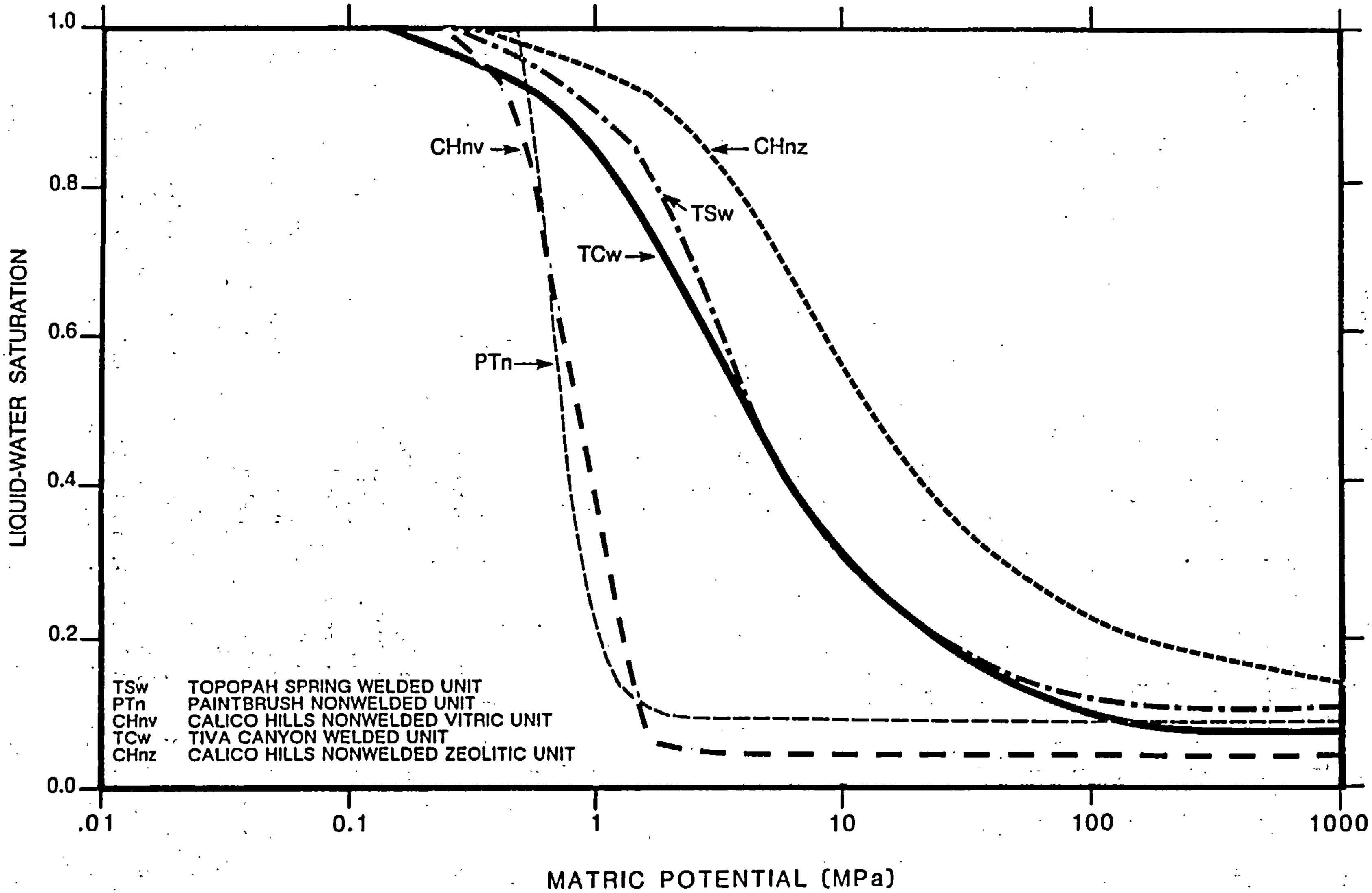


Figure 3-33. Moisture-retention curves for the hydrogeologic units within the unsaturated zone at Yucca Mountain. Modified from Peters et al. (1984).

Liquid-water storage within fractures probably is insignificant, but the flow of liquid water within and across fractures is not yet well understood. Theoretical models for liquid-water flow in single fractures have been developed (Wang and Narasimhan, 1985, and Montazer and Harrold, 1985) but have not been field or laboratory tested. The intact-fracture test to be performed in the exploratory shaft at Yucca Mountain (Section 8.3.1.2.2.4) is designed to investigate in detail the mechanics of flow in a single fracture under variable conditions of saturation and stress. Fractures may or may not impede liquid-water flow at low matrix saturations, but longitudinal flow within the fractures may dominate liquid-water flow above some critical matrix saturation (Montazer and Wilson, 1984; and Klavetter and Peters, 1986). Consequently, at high matrix saturations the fracture systems within the densely welded, fractured hydrogeologic units (e.g., the TCw and TSw units) and within the fault zones may become highly efficient pathways for liquid-water flow. Liquid-water flow within the fractures may be Darcian with an appropriately defined potential and hydraulic conductivity (for example, under the parallel-plate, cubic-law approximation for flow in single fractures), but, as pointed out previously, the potential in the fractures need not be equal to the matrix potential in the rock matrix, especially under highly transient conditions (Klavetter and Peters, 1986).

Considerable attention must be given to the problem of how best to represent the hydrologic properties and hydrologic response of a highly fractured porous medium. Separate treatment of the matrix and the individual fractures is not practical. In the first place, no way is known to generate a complete set of fracture location and geometry data. Secondly, if the Topopah Spring welded unit has a mean fracture density of 20 fractures/m^3 and has a mean thickness of 300 m over the approximately 7 x 10^6 m^2 area of the central Yucca Mountain block, then one would have to consider flow in approximately 4 x 10^{10} discrete fractures. Consequently, the practical alternative is to regard the matrix and fractures as constituting either separate but overlapping continuum systems or as a single composite continuum system. These approaches assume that the matrix and fracture properties can be represented as spatial averages over rock mass volumes whose linear dimensions are very much smaller than the thickness of the hydrogeologic unit but sufficiently large to include a representative, statistical sample of hydraulically connected fractures. The rock mass volume over which the averaging is performed is commonly designated as a representative elementary volume (REV) (Bear, 1972). The macroscopic continuum approach for fractures and rock matrix has been examined theoretically by Klavetter and Peters (1986), who conclude that it appears to be applicable to the unsaturated, fractured tuffs at Yucca Mountain. Specifically, they consider a "composite-porosity" model which describes fluid movement in a single continuum composed of both matrix material and fractures. This approach would not be applicable to sparsely fractured media or to media in which the mean fracture apertures exceeded a few millimeters and, thus, for which the medium would cease to be approximated by a bundle of capillary tubes. One principal objective of the bulk-permeability test, which is to be performed within the exploratory shaft as described in Section 8.3.1.2.2.4, is to field-test the REV hypothesis as it may apply to the fractured Topopah Spring welded unit at the potential repository horizon.

Preliminary results based on a dual-porosity, porous-medium-equivalent representation for fractured hydrogeologic units have been reported by

Montazer and Wilson (1984), Wang and Narasimhan (1985), and Klavetter and Peters (1986). The dependence of relative hydraulic conductivity on liquid-water potential in a fractured porous medium under the composite dual-porosity continuum hypothesis may be expected to exhibit the qualitative appearance shown in Figure 3-34. At low matrix saturations, little or no water moves longitudinally within the fracture openings, and the effective hydraulic conductivity is controlled by that of the fracture-bounded matrix blocks. As the matrix approaches complete saturation, however, the movement of water within and along the fracture aperture rapidly becomes more efficient so that at complete saturation the fractures may be dominant contributors to the net hydraulic conductivity. The relative contributions of fractures and matrix to the net effective hydraulic conductivity depend on the fracture frequency, aperture-size distribution, and degree of interconnectivity. The hydrogeologic unit TSw exemplifies the extremes that may be encountered. This unit has a matrix saturated hydraulic conductivity of about 10^{-11} m/s and a fracture density of 8 to 40 fractures/m^3 (Table 3-26). In well J-13, the Topopah Spring unit is fully saturated. It is the major source of water to the well and has an estimated net bulk, presumably fracture-controlled, hydraulic conductivity of about 8 x 10^{-6} m/s (Thordarson, 1983).

A further complication arises inasmuch as the hydrogeologic units may be anisotropic with respect to intrinsic permeability and thus to hydraulic conductivity. Data are presently insufficient to perform an adequate assessment. Because chemical alteration can be expected to destroy preferred orientations of rock properties, the matrix properties of the altered, zeolitized CHnz unit probably are largely isotropic. The fracture and fault systems within the densely welded units, however, probably introduce an inherent anisotropy wherever they are present and contribute significantly to moisture or pore-gas flow. Two principal fracture sets have been identified within the Yucca Mountain block (Scott et al., 1983). One set strikes north-northwest and the other strikes north-northeast, and both fracture sets exhibit steep to vertical dips. Most of the faults bounding and within the Yucca Mountain block are typical Basin and Range style high-angle normal faults that dip to the west, strike to the north, and exhibit small individual displacements (2 to 5 m). The Solitario Canyon fault, which bounds Yucca Mountain on the west, is a northward-striking high-angle normal fault that dips to the west and has a displacement ranging from 20 to 200 m along its trace. The Ghost Dance fault within the Yucca Mountain block is likewise a west-dipping, north-striking normal fault with a displacement of about 25 m. These faults and their associated fracture zones in the more competent hydrogeologic units probably introduce a fundamental preferential directional control on moisture movement, whether these fault zones act as conduits for or barriers to flow. Quantitative data by which to characterize rock-matrix and fracture-induced anisotropy is currently lacking but will be examined by field testing in surface-based boreholes and in the exploratory shaft and by laboratory measurements on cores and on rock samples obtained during excavation of the exploratory shaft facility, as described in Section 8.3.1.2.

Available data on the magnitude and distribution of moisture content within the unsaturated zone are scanty and incomplete. Drill cuttings were collected continually and their gravimetric moisture contents measured during the drilling of test boreholes USW UZ-1 and USW UZ-6 (Whitfield, 1985). The resulting moisture-content profiles are shown in Figure 3-35 for drillhole

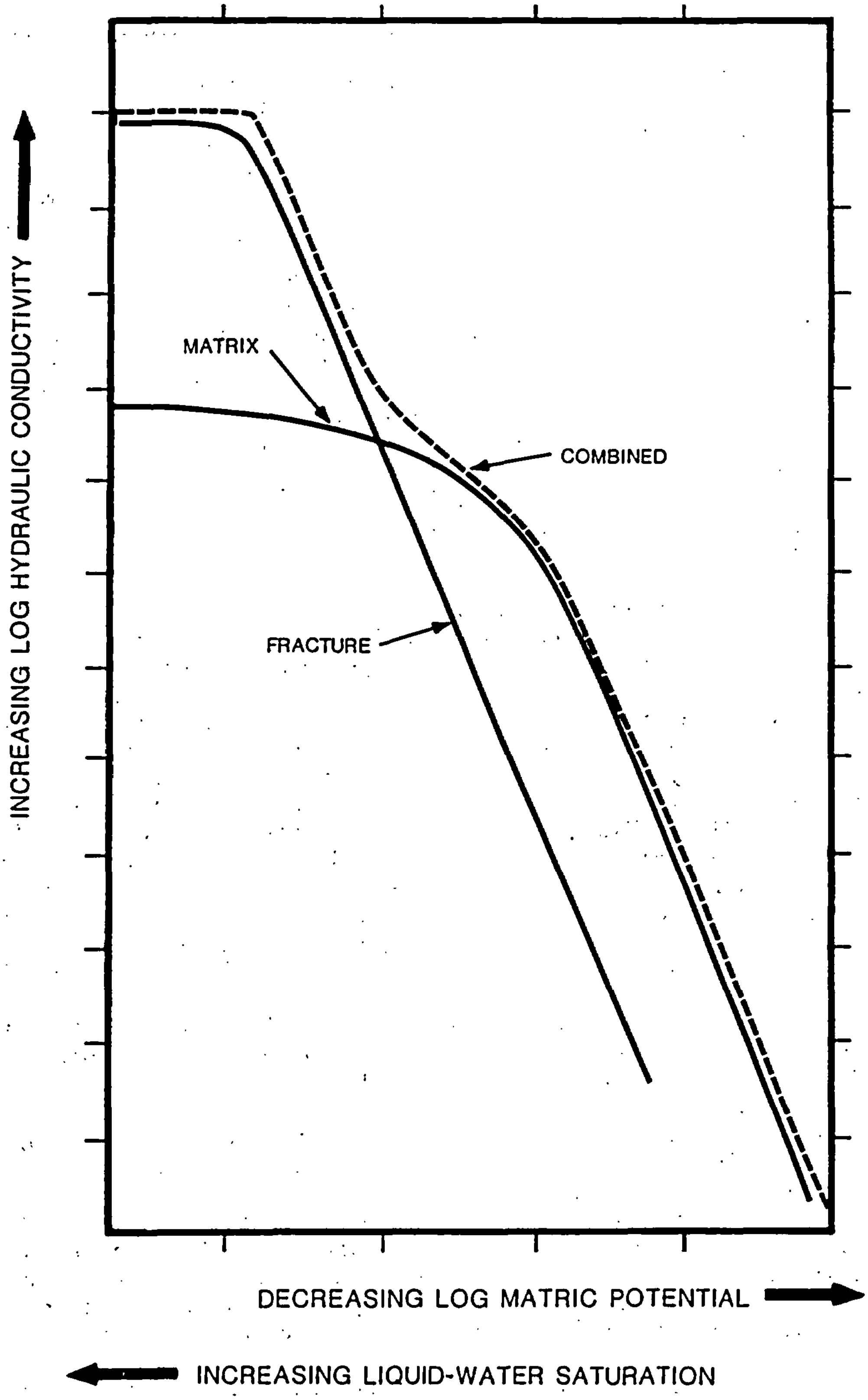


Figure 3-34. Idealized hydraulic-conductivity characteristic curve for a composite (fracture-matrix) porous medium. Modified from Montazer and Wilson (1984).

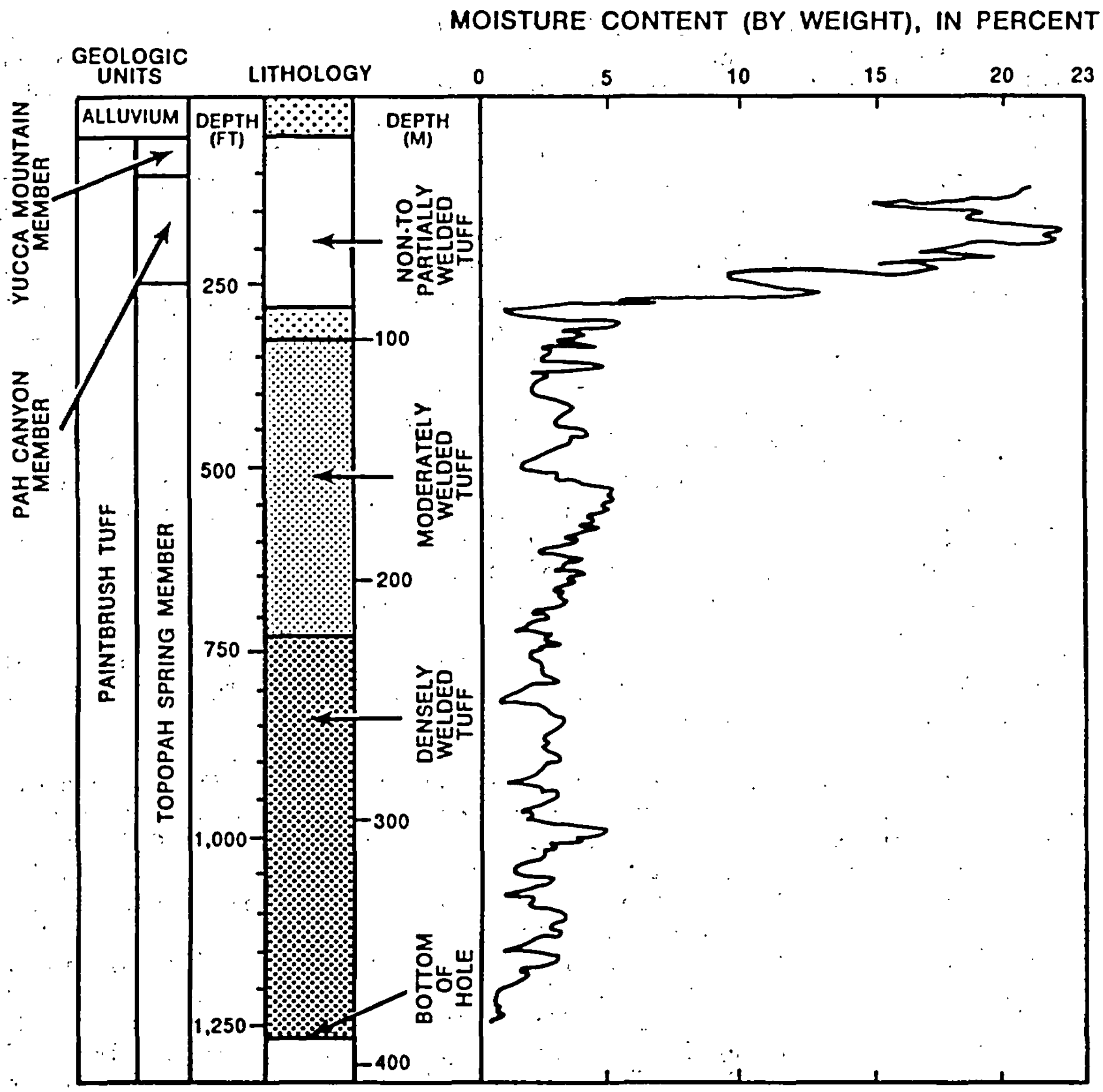


Figure 3-35. Moisture content of drill cuttings from borehole USW UZ-1. Modified from Whitfield (1985).

USW UZ-1 and in Figure 3-36 for drillhole USW UZ-6. The two profiles are similar in that they indicate relatively high moisture contents in the nonwelded tuff intervals and lower moisture contents in the Tiva Canyon and Topopah Springs welded units. Both profiles exhibit some degree of irregularity or scatter. The scatter within a given profile may be due to (1) inherent variations in moisture content or (2) undetermined experimental errors. Differences between the two profiles may also be attributed to these two causes. The data indicate, for example, that the moisture content within the Paintbrush nonwelded (PTn) hydrogeologic unit has a representative mean value in the two wells of about 0.2 kg/kg, which, assuming a mean porosity of 0.43 and a grain density of about 2,400 kg/m^3 (Table 3-26, Section 3.9.2.1), yields a mean saturation of about 0.6 for this unit. The interval of the Tiva Canyon welded (TCw) unit penetrated in drillhole USW UZ-6 has a mean moisture content of about 0.025 kg/kg, which, with a mean porosity of 0.1 and a mean grain density of about 2,500 kg/m^3 (Table 3-26), yields a mean saturation for this unit of about 0.6. The Topopah Spring welded (TSw) hydrogeologic unit has a mean moisture content of about 0.025 kg/kg in drillhole USW UZ-1 and about 0.02 kg/kg in drillhole USW UZ-6. Using a mean porosity of 0.12 and a grain density of about 2,600 kg/m^3 for this unit (Table 3-26), a mean saturation is obtained for the TSw unit of about 0.5 in drillhole USW UZ-1 and about 0.4 in drillhole USW UZ-6. These very tentative results generally are consistent with the ambient mean saturations of 0.61 for the PTn unit, 0.67 for the TCw unit, and 0.65 for the TSw unit reported by Montazer and Wilson (1984).

Using the moisture-retention curves shown in Figure 3-33, these estimates of in situ saturations may be converted into corresponding matric potentials. For example, if the saturation in the PTn unit is 0.6, the curve in Figure 3-33 for this unit implies a matric potential of about -0.75 Mpa, a value that is compatible with the range of matric potentials for this unit implied by the matric-potential data obtained to date from drillhole USW UZ-1 (Figures 3-30 and 3-31). However, if the saturation in the TSw unit is 0.5, the curve for this unit in Figure 3-33 implies a corresponding matric potential of about -7 MPa, a value quite different from the mean of about -0.3 MPa for the TSw unit implied by from the matric-potential data in drillhole USW UZ-1 (Figures 3-30 and 3-31). This apparent discrepancy emphasizes the need for continued monitoring of ambient hydrologic conditions within the unsaturated zone at Yucca Mountain, as well as for the direct laboratory measurement of the hydrologic properties for statistically large samples of cores, drill cuttings, and bulk-rock samples taken from within each of the hydrogeologic units at numerous locations within Yucca Mountain.

Under transient moisture-flow conditions, moisture may be taken into or released from storage within the system, and parameters describing the moisture-storage properties of the system must be supplied as part of the hydrologic properties. Storativity is defined by Bear (1972) to be the change in volume of liquid water storage per unit volume of bulk rock mass upon unit change of liquid-water potential. The rate at which the quantity of water held in storage changes with time is equal to the product of storativity and the time rate of change of liquid-water potential. In partially saturated media, storativity depends upon (1) the relations between ambient matrix and fracture saturations and the liquid-water potential in the matrix and fractures; (2) the liquid-water compressibility; and (3) the effective bulk compressibility appropriate to the rock matrix and the fractures.

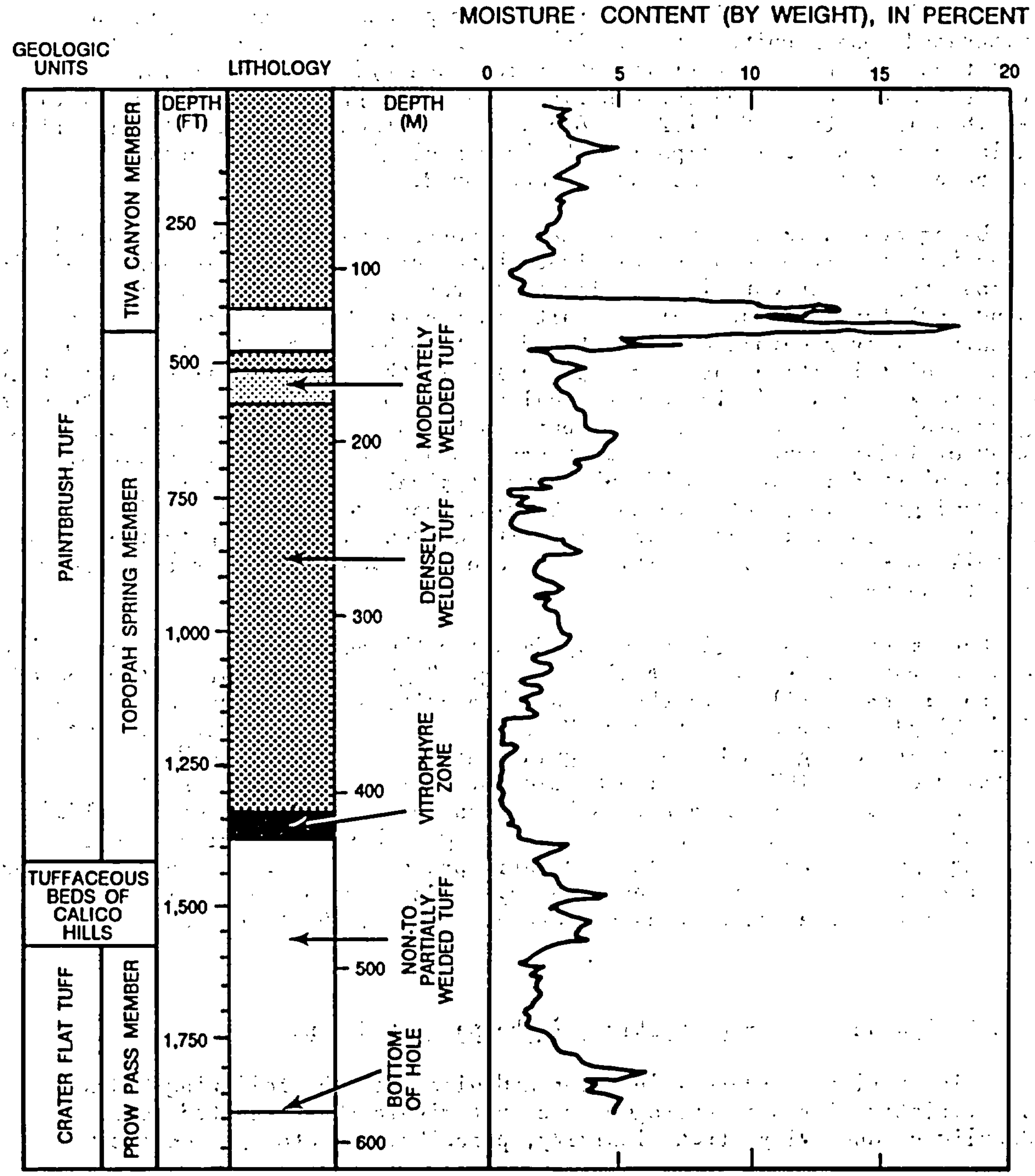


Figure 3-36. Moisture content of drill cuttings from borehole USW UZ-6. Modified from Whitfield (1985).

Consequently, specification of moisture storage and movement within the unsaturated zone requires the availability of hydro-mechanical-thermal properties and their spatial variation for each hydrogeologic unit. These data are to be determined through field, laboratory, and theoretical studies described in Sections 8.3.1.2 and 8.3.1.15. Thermomechanical data presently available for the rocks composing the hydrogeologic units at Yucca Mountain have been compiled and summarized in Section 2.4.

Using approximate values for the rock-matrix and fracture mechanical properties, Klavetter and Peters (1986) have performed a preliminary analysis of capacitance (conceptually similar to storativity but with different dimensions) for the hydrogeologic units in the unsaturated zone at Yucca Mountain. They regarded each fractured unit to be represented as a composite porous medium in which the matric potential in the fractures is equal to that in the rock matrix. Their results, calculated for the TSw unit, are shown in Figure 3-37, which shows the contributions to the total capacitance due to a number of independent storage mechanisms. Under the assumed conditions, the results plotted in Figure 3-37, which are typical of those for the other hydrogeologic units, indicate that changing fracture and rock-matrix saturations dominate storage capacity with decreasing matric potential while the bulk rock-matrix compressibility becomes the dominant contributor near complete saturation.

Fundamental hydrologic-property data for the bulk-gas flow system within the unsaturated zone are presently lacking. Highly preliminary estimates of in situ air permeability in the TCw and PTn units at boreholes USW UZ-1 and USW UE-25a#4 have been reported by Montazer et al. (1985). Downhole pore-gas pressures are being monitored at regular intervals in borehole USW UZ-1 (Montazer et al., 1985; see also Section 3.9.1.1.1), and the results of pore-gas sampling and chemical analyses have been reported by Yang et al. (1985a) (Section 3.9.1.3). An extensive program of gas-phase monitoring, chemical sampling, gas-tracer studies and pneumatic-property determinations is planned as part of the surface-based, exploratory shaft, and laboratory investigations of the unsaturated zone and are described in Section 8.3.1.2.2.

3.9.2.2 Hydraulic characteristics of the saturated zone

This section presents values for and discusses the following hydraulic characteristics for each hydrogeologic unit within the saturated zone: hydraulic conductivity, transmissivity, porosity, and storage coefficient.

3.9.2.2.1 Hydraulic conductivity and fractures

Analytical approaches to the determination of hydraulic conductivity of rocks in the saturated zone for the Yucca Mountain site have involved variations of Theis equations, which are based on Darcian flow, and assumptions of nonsteady discharge of water from wells. The specific or detailed nature of data from each test hole has varied; pumping responses have varied because of variations of hydraulic conditions among well sites; and conceptual ideas of the nature of the systems have evolved as experience

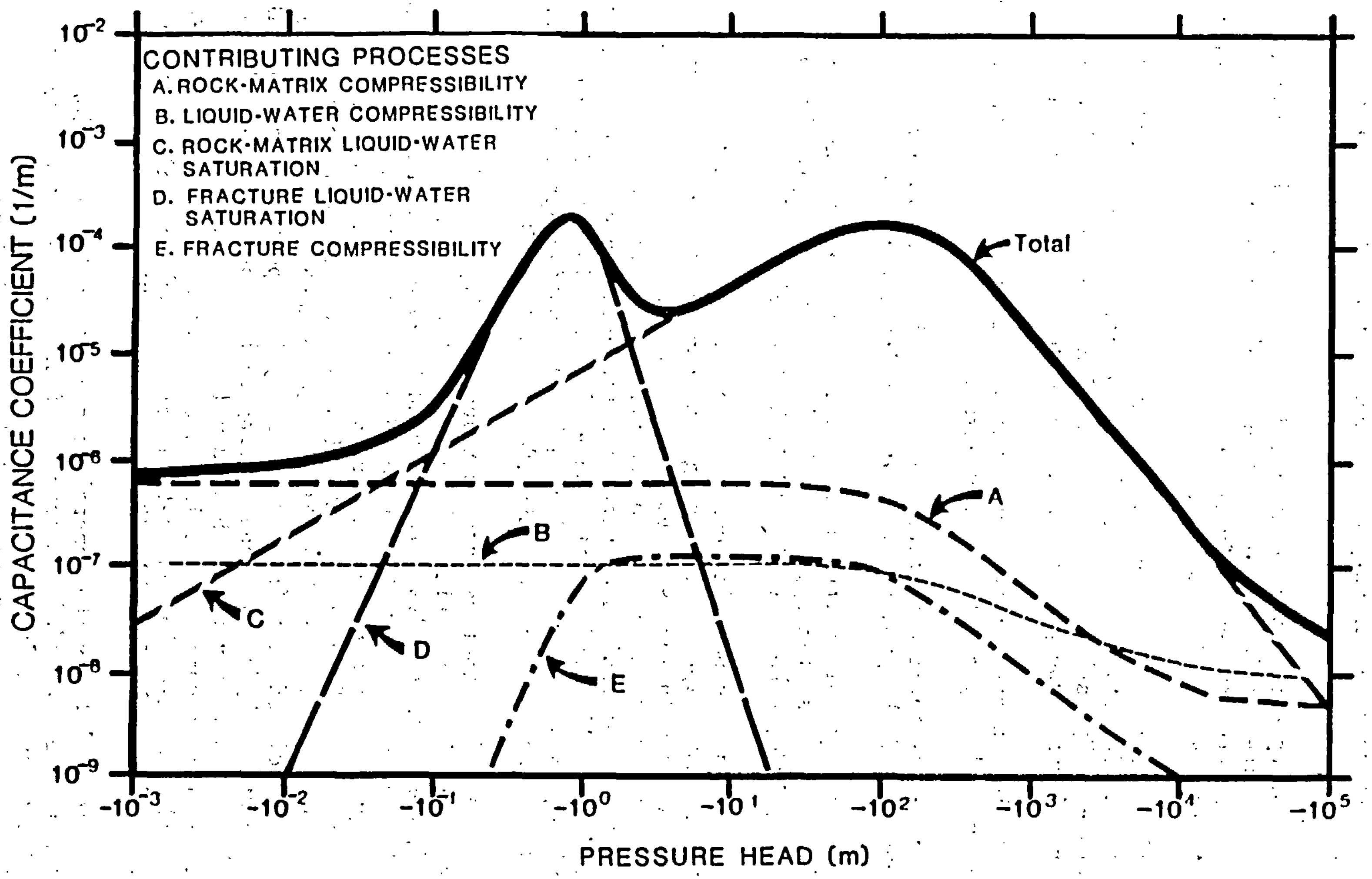


Figure 3-37. Computed capacitance coefficient versus pressure head for the Topopah Spring welded (TSw) hydrogeologic unit. Modified from Klavetter and Peters (1986).

has been gained, although analysis of the data for each well site has been based on assumptions that are generally common to each:

1. The tested rock has primary matrix porosity and is homogeneous and isotropic.

2. The secondary porosity is controlled by fractures. The fractures generally are vertical or very steep within the saturated zone. The volume of water stored in fractures is relatively small in comparison to that stored in matrix pores.

3. The flow directly into the well is through fractures only, but within the formation there is flow from matrix pores to the fractures. Hydraulic conductivity of fractures is probably several orders of magnitude greater than the conductivity of the matrix.

4. A sufficient number of fractures has been intercepted by the pumped well to yield representative responses.

5. The distances between fractures are small in comparison with the dimensions of the ground-water system being considered.

6. The orientation of fractures is assumed to be random, on a large scale, and the system appears to be laterally isotropic (Craig and Robison, 1984; Lahoud et al., 1984; Rush et al., 1984).

The above is a double-porosity concept; however, the parameters necessary to analyze fracture aperture, spacing, and continuity were not available, and porous-media solutions were used in calculations of bulk values of in situ transmissivity and hydraulic conductivity shown in Table 3-27 (in which transmissivity for individual stratigraphic units ranges from 0.001 to 276 m^2/day, and hydraulic conductivity ranges from 2 x 10^{-6} to 2.3 m/day). Where appropriate, data will be reevaluated by alternative approaches, such as those based on fracture-flow concepts (Section 8.3.1.2.3).

In situ values of parameters such as transmissivity or hydraulic conductivity were determined from single-hole tests, the limitations of which are recognized; observation holes were not used because none that were deep enough were also close enough that they could be expected to show responses that would be separable from normal background variations due to earth tides and barometric affects. However, Moench (1984) (1) evaluated responses from an observation hole, 100 m from UE-25b#1 (he used a double-porosity conceptual model), (2) concluded that fracture skin may be important, and (3) calculated fracture system hydraulic conductivity to be about 10^{-5} m/s and block system hydraulic conductivity to be about 2 x 10^{-6} m/s). Also, as the precision of water-level measurements is increased (Section 3.9.1.1.2), aquifer tests that include responses in observation holes at substantial distances from the pumped well may be feasible (Section 8.3.1.2.3).

In the single-well tests the general approach to data collection was the same for each hole. It included measurement of drawdown and recovery of water levels due to pumping from the entire hole (or a major interval in it); a borehole-flow survey while pumping, to define individual productive zones;

Table 3-27. Preliminary[a] summary of hydrologic characteristics of major stratigraphic units in the vicinity of Yucca Mountain (page 1 of 2)

		In situ (field) analyses					Laboratory analyses (cores)					
							Saturated matrix hydraulic conductivity		Matrix porosity[e]			
Stratigraphic unit	Typical character	Saturated thickness (m)	Transmissivity[b] (m^2/d)	Average hydraulic conductivity[c] (m/d)	Well or hole tested	Reference[d]	m/d	No. of samples	%	No. of samples	Well or hole analyzed	Reference[d]
Topopah Spring Member	Moderately to densely welded tuff	167	120	0.7	J-13	7	$3x10^{-7}$ to $2x10^{-4}$	5	4 - 33	5	J-13	7
							$7x10^{-7}$ to $5x10^{-4}$	18	6 - 30	24	UE-25a#1	1
							$8x10^{-7}$	1	12	1	UE-25b#1	4
Tuffaceous beds of Calico Hills	Zeolitized, nonwelded tuff, vitric tuff	148	(82)	0.5	UE-25b#1	4	$4x10^{-6}$ to $3x10^{-4}$	6	20 - 34	7	UE-25a#1	1
Prow Pass Member of Crater Flat Tuff	Nonwelded to moderately welded tuff	116	167	1.44	USW H-1	2	$6x10^{-6}$ to $1x10^{-4}$	3	28 - 29	3	USW H-1	6
		135	150	1.1	USW H-1	6	$2x10^{-5}$ to $1x10^{-3}$	8	10 - 25	12	UE-25a#1	1
		174	36 - 142[f]	0.2-0.8[f]	USW H-4	9	$6x10^{-7}$ to $1x10^{-3}$	5	17 - 30	18	USW G-4	5
		150	(65)	0.4	UE-25b#1	4						
		111	14	0.1	UE-25p#1	3						
Bullfrog Member of Crater Flat Tuff	Nonwelded to densely welded tuff	125	0.8	0.006	USW H-1	6	$3x10^{-5}$ to $1x10^{-3}$	10	19 - 34	9	USW H-1	6
		119	70 - 276[f]	0.6-2.3[f]	USW H-4	9	$2x10^{-4}$ to $1x10^{-3}$	3	17 - 34	3	UE-25a#1	1
		159	(65)	0.4	UE-25b#1	4	$2x10^{-4}$ to $5x10^{-4}$	2	24 - 27	6	USW G-4	5
		132	(7)	0.05	UE-25p#1	3						
Tram Member of Crater Flat Tuff	Nonwelded to moderately welded ash-flow and bedded tuffs	284	$2x10^{-3}$	$7x10^{-6}$	USW H-1	6	$4x10^{-6}$ to $4x10^{-4}$	9	18 - 26	9	USW H-1	6
		354	0.7	0.002	USW H-3	8						
		352	70 - 276[f]	0.2-0.8[f]	USW H-4	9						
		183	(3.3)	0.02	UE-25p#1	3						
Lithic Ridge Tuff and older tuffs	Partially welded ash-fall tuffs	594	0.001	$2x10^{-6}$	USW H-1	6	$6x10^{-5}$ to $3x10^{-4}$	2	9 - 17	2	USW H-1	6
		110	0.1	$1x10^{-3}$	USW H-3	8						
		371	>10	>0.03	UE-25p#1	3						

Table 3-27. Preliminary[a] summary of hydrologic characteristics of major stratigraphic units in the vicinity of Yucca Mountain (page 2 of 2)

Stratigraphic unit	Typical character	In situ (field) analyses: Saturated thickness (m)	Transmissivity[b] (m²/d)	Average hydraulic conductivity[c] (m/d)	Well or hole tested	Reference[d]	Laboratory analyses (cores): Saturated matrix hydraulic conductivity m/d	No. of samples	Matrix porosity[e] %	No. of samples	Well or hole analyzed	Reference[d]
Lone Mountain Dolomite and Roberts Mountain Formation	Carbonate rocks Paleozoic age (lower) carbonate aquifer of Winograd and Thordarson, 1975)	>561	108	0.2	UE-25p#1	3						

[a]Interpretive analyses from in situ testing at some drillholes are not completed yet, including those from drillholes USW G-4, USW H-6, and UE-25c#1,2,3.

[b]Determined from pumping tests, borehole-flow surveys, and slug-injection tests; parentheses indicate approximate value because reported values reflect more than one stratigraphic unit. See references cited for details of individual drillholes tested.

[c]Obtained by dividing transmissivity by saturated thickness, which in some cases may not agree with values reported in the cited reference. Productive zones are typically thin, fractured intervals rather than a generally-uniform rock matrix; therefore, the porous-media concept of hydraulic conductivity is not necessarily appropriate.

[d]1, Anderson (1981); 2, Barr (1985); 3, Craig and Robison (1984); 4, Lahoud et al. (1984); 5, Peters et al. (1984); 6, Rush et al. (1984); 7, Thordarson (1983); 8, Thordarson et al. (1984); 9, Whitfield et al. (1985).

[e]Chapter 2 - Geoengineering.

[f]Lower value based on straight-line method of pumping-test analysis; higher value based on Theis-recovery method (see Whitfield et al. (1985)).

and measurement of head changes of selected (straddled) intervals due to removal (by swabbing) or injection (falling head) of water.

Claassen and White (1979) studied the possible extent of fracture control on the Rainier Mesa ground-water system in the northern part of the NTS; they concluded that the hydraulic characteristics of the Paintbrush Tuff are controlled by fracture porosity. Blankennagel and Weir (1973) observed, through extensive hydrologic testing of Pahute Mesa, that welded tuff and rhyolite have larger bulk hydraulic conductivities than nonwelded or bedded tuff because the former are brittle and fracture readily.

Interconnection of some fractures in welded tuffs beneath Pahute Mesa and Yucca Mountain was demonstrated by hydrologic tests in holes that included slug-injection or withdrawals of water of isolated depth intervals, pumping tests, and borehole-flow surveys to determine intervals that yield water. The volume of water removed during pumping tests is many times greater than that expected from fractures near the drill holes (Blankennagel and Weir, 1973; Rush et al., 1984), which may indicate that these fractures are connected to more distant ones, although there may also be some contribution from the rock matrix.

Hydraulic conductivity of tuffs may decrease with increasing depth; welded tuffs are generally less conductive than rhyolites at the same depth (Waddell et al., 1984). At greater depths, formation of minerals in fractures (commonly clays, silica, calcite, zeolites, or iron and manganese oxides) or closing of fractures because of greater lithostatic stresses tend to decrease the aperture of fractures. Rush et al. (1984) show that, in drillhole USW H-1, bulk hydraulic conductivity (determined from pumping tests) is substantially greater than matrix hydraulic conductivity (determined from cores) for the shallower rocks, but at greater depths the bulk and matrix hydraulic conductivity are approximately equivalent. They concluded that there may be no fracture flow below a depth of 790 m in rocks penetrated by drillhole USW H-1 because the greater overburden pressure decreases fracture porosity. It is not known if these conditions prevail throughout the Yucca Mountain area.

Controls on fracture density are not clear. Besides being a function of rock type, fracture density is a function of structural setting. A zone of increased fracturing and faulting on the southeastern and eastern sides of Yucca Mountain has been mapped (Scott and Bonk, 1984). Another feature evident from surface mapping is that fracture density decreases in the northern part of Yucca Mountain, where displacement and number of faults are less than in the southern part. Fracture density is presumed to increase near faults of large displacement, and a corresponding increase in local bulk hydraulic conductivity could be expected. Plans to examine this are presented in Section 8.3.1.2.3.

The probable importance of flow in fractures in the saturated zone is indicated by two lines of evidence. First, hydraulic conductivity of the matrix, as measured on cores and by slug-injection tests of nonproductive parts of drillholes, is much lower than in situ conductivity measurements in productive parts of drillholes (Rush et al., 1984). Second, productive zones, as determined by borehole-flow and temperature surveys performed during pumping tests, correlate with fracture zones determined from televiewer and caliper logs (Lahoud et al., 1984; Rush et al., 1984). Preliminary indications from studies in progress at test holes UE-25c#1, 2, and 3 indicate that hydraulic conductivities of fractures are several orders of magnitude greater than matrix conductivities (Waddell et al., 1984; SCP Section 8.3.1.2.3).

Two sets of faults and fractures are present at Yucca Mountain (Scott et al., 1983). The first set strikes north-northwest and dips steeply to the west. The second strikes north-northeast and also dips steeply to the west. The minimum compressive stress is oriented N. 50 to 60 degrees W., which is coincident with the regional direction of tectonic extension (Carr, 1974). Fractures with these orientations may tend to be closed by tectonic stresses, whereas fractures with orientations of N. 30 to 40 degrees E. may tend to be more open. Therefore, the system may not be hydraulically isotropic because the north-northeast-striking fracture set may be more transmissive. Multiple-well hydraulic tests in the vicinity of drillhole UE-25c#1 are planned to test the hypothesis that fracture orientation may tend to control the direction or rate of ground-water flow (Section 8.3.1.2.3).

Using fracture frequency and orientation data from drillhole USW H-4, Erickson and Waddell (1985) calculated the probable shape and orientation of the hydraulic-conductivity ellipsoid at that site; they determined that the plane containing the two larger principal axes strikes northeast and is nearly vertical. The hydraulic conductivity in this plane is 5 to 7 times that of the smallest principal hydraulic conductivity.

Most fractures are steeply dipping, and vertical permeability within a single cooling unit may be approximately the same as maximum horizontal permeability within a single cooling unit. However, because of nearly horizontal layering in ash-flow tuffs, due to emplacement and cooling mechanics, and because of the presence of bedded, nonwelded tuffs, vertical variations in fracture frequency probably occur (Waddell et al., 1984). Some indication of vertical hydraulic conductivity may be obtainable from the fracture-orientation testing in the vicinity of drillhole UE-25c#1 (Section 8.3.1.2.3).

Vertical and horizontal interconnectivity of fractures was demonstrated by a pumping test of drillhole UE-25b#1, which was pumped for 29 days at about 12 L/s from the interval 853 to 914 m (lower Bullfrog to upper Tram Member). The results of a similar borehole-flow survey are shown on Figure 3-38. A sodium bromide tracer was placed in drillhole UE-25a#1, which is 107 m away from drillhole UE-25b#1 and is open to the formation from the water level (470 m) to total depth of 762 m (tuffaceous beds of Calico Hills to upper Bullfrog Member). Breakthrough of the tracer in UE-25b#1 occurred in two days, and above-background concentrations continued for the next 26 days of pumping (Waddell, 1984; Waddell et al., 1984).

Knowledge of the role of fractures in controlling paths and velocities of ground-water flow at Yucca Mountain is insufficient to characterize the flow system adequately. An understanding is also needed of the applicability of the concepts of porous-media equivalents for describing the flow system. Improved understanding of these factors is expected to come from planned tracer tests at Yucca Mountain (Section 8.3.1.2.3.1). In addition, other methods of data analysis will be evaluated (Section 8.3.1.2.3.1).

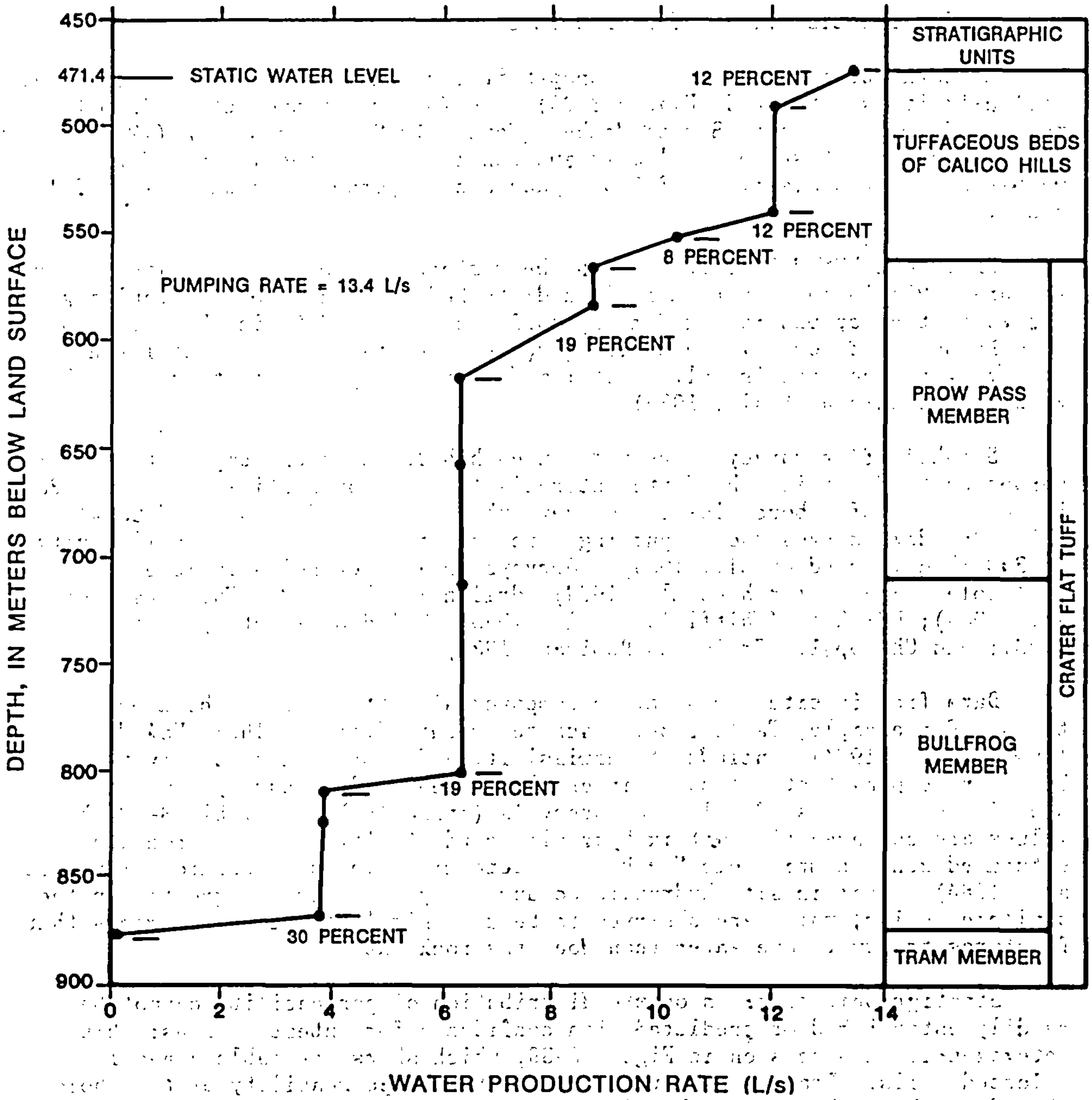


Figure 3-38. Borehole-flow survey of drillhole UE-25b#1 (when hole was at total depth of 1,220 m). Modified from Lahoud et al. (1984).

3.9.2.2.2 Transmissivity and hydraulic conductivity

Beneath Yucca Mountain, the Topopah Spring Member is unsaturated, but at well J-13 it is saturated (Figure 3-25), and most water production from the well is from the Topopah Spring Member (Young, 1972). Thordarson (1983) analyzed pumping tests of well J-13 and concluded that the Topopah Spring Member has a transmissivity of 120 m^2/day and a hydraulic conductivity of 1.0 m/day.

Drillhole USW H-3 is located on the western edge of the repository block (Figure 3-28) in an area relatively undisturbed by fracturing and faulting, and where the Topopah Spring Member, tuffaceous beds of Calico Hills, Prow Pass Member, and most of the Bullfrog Member are unsaturated. Total transmissivity at the site is only about 1 m^2/d, virtually all of it from the Tram Member (Thordarson et al., 1985).

Borehole-flow surveys were made in each hole in which pumping tests were conducted to determine the depth intervals that are productive. Figure 3-38 is an example of a borehole-flow survey, this one from drillhole UE-25b#1, in which drawdown curves due to pumping were used to calculate a transmissivity of 340 m^2/d (Lahoud et al., 1984). Surveys from other holes include drillhole USW H-1, (Rush et al., 1984); drillholes USW H-3, (Thordarson et al., 1984); USW H-4, (Whitfield et al., 1985); USW H-5, (Bentley et al., 1983); and UE-25p#1, (Craig and Robison, 1985).

Data from in situ tests can be compared with those from laboratory tests. For example, Table 3-28, which shows data from drillhole USW H-1 (Rush et al., 1984), includes transmissivity and hydraulic conductivity, based on pumping tests of major intervals, borehole-flow surveys, and slug-injection tests of selected intervals (straddles). In Table 3-29 these values are compared with matrix hydraulic conductivity of cores from the saturated zone in drillhole USW H-1, as determined in the laboratory (Rush et al., 1984). That in situ hydraulic conductivity is generally greater in the shallower units, which are observed to be more highly fractured suggests that fractures transmit more water than does the rock matrix.

Stratigraphic controls on the distribution of permeability cannot be readily established or predicted with confidence for untested areas; this heterogeneity can be seen in Figure 3-39, which shows permeable zones for selected wells. Fractures contribute more to the permeability of test holes than does the rock matrix; therefore, productive intervals are determined by the depths at which holes intercept transmissive fractures. The dip of most fractures is very steep, and drillholes are nearly vertical; therefore, a statistically significant number of fractures is not likely to be intercepted by a vertical drilling program of reasonable design. This bias will be partially ameliorated through data gathered from horizontal boreholes extending off the exploratory shaft.

In the following several paragraphs, the saturated hydraulic characteristics of each major stratigraphic unit beneath the Yucca Mountain site is discussed.

Table 3-28. Transmissivity and average hydraulic conductivity at well USW H-1, based on pumping tests, borehole-flow surveys, and slug-injection tests[a]

Depth interval (m)	Transmissivity (m^2/d)	Horizontal average hydraulic conductivity (m/d)
	PROW PASS MEMBER	
572-597	74	3
597-616	18	1
616-652	40	1
652-653	18	18
653-688	≤ 1	$\leq 3 \times 10^{-2}$
687-694	1×10^{-1}	1×10^{-2}
687-697	1×10^{-1}	1×10^{-2}
	PROW PASS AND BULLFROG MEMBERS	
694-736	1×10^{-2}	$\leq 2 \times 10^{-4}$
	BULLFROG MEMBER	
736-741	6×10^{-1}	1×10^{-1}
741-758	2×10^{-1}	1×10^{-2}
758-792	1×10^{-2}	3×10^{-4}
792-811	$\leq 3 \times 10^{-3}$	$\leq 2 \times 10^{-4}$
	BULLFROG AND TRAM MEMBERS	
811-926[b]	5×10^{-3}	4×10^{-5}
	TRAM MEMBER AND FLOW BRECCIA	
926-1,200[b]	$\leq 2 \times 10^{-3}$	$\leq 7 \times 10^{-6}$

Table 3-28. Transmissivity and average hydraulic conductivity at well USW H-1, based on pumping tests, borehole-flow surveys, and slug-injection tests[a] (continued)

Depth interval (m)	Transmissivity (m^2/d)	Horizontal average hydraulic conductivity (m/d)
	FLOW BRECCIA AND LITHIC RIDGE TUFF	
1,200-1,407[b]	$\leq 2 \times 10^{-3}$	$\leq 1 \times 10^{-5}$
	LITHIC RIDGE TUFF AND OLDER TUFFS	
1,407-1,621[b]	8×10^{-4}	4×10^{-6}
	OLDER TUFFS	
1,621-1,829[b]	2×10^{-4}	1×10^{-6}

[a]Source: Rush et al. (1984).
[b]Values for interval computed by difference from overlapping injection-test intervals.

Table 3-29. Comparison of hydraulic-conductivity values from in situ tests with core-sample analyses

Stratigraphic unit	Selected depth interval from Table 3-28 (m)	Average hydraulic conductivity (m/d): Total, from in situ tests (Table 3-28)	Average hydraulic conductivity (m/d): Matrix, from core analyses[a]
Prow Pass Member	616-652	1	[b]8×10^{-5}
Prow Pass and Bullfrog members	694-736	$<2 \times 10^{-4}$	[c]3×10^{-4}
Bullfrog Member	758-792	3×10^{-4}	[d]4×10^{-4}

Table 3-29. Comparison of hydraulic-conductivity values from in situ tests with core-sample analyses (continued)

Stratigraphic unit	Selected depth interval from Table 3-28 (m)	Average hydraulic conductivity (m/d)	
		Total, from in situ tests (Table 3-28)	Matrix, from core analyses[a]
Bullfrog and Tram members	811-926	4×10^{-5}	[c]4×10^{-5}
Tram Member and flow breccia	926-1200	$<7 \times 10^{-6}$	[e]2×10^{-4}

[a]Core-sample analyses from Rush et al. (1984).
[b]Average for three core-sample analyses.
[c]Average for four core-sample analyses.
[d]Average for five core-sample analyses.
[e]Average for six core-sample analyses.

The Topopah Spring Member of the Paintbrush Tuff which has saturation only east of the repository block (Figure 3-25) has a high hydraulic conductivity. Many fractures have been observed in cores and in television surveys; lithophysal cavities are common in some zones (Scott et al., 1983). Problems related to loss of drilling fluids while penetrating the Topopah Spring Member are common. Matrix hydraulic conductivity of the unit is small. Thordarson (1983) reported hydraulic conductivities from cores at well J-13 that range from 2×10^{-4} to 8×10^{-7} m/d; however, the Topopah Spring Member is fractured, has an average in situ hydraulic conductivity of 0.7 m/d, and is the most productive unit penetrated by the well.

The tuffaceous beds of Calico Hills are above the water table in most hydrologic test holes near Yucca Mountain. In drillhole UE-25p#1 the unit is mostly saturated but poorly permeable; during a pumping test, a borehole-flow survey indicated the unit yielded less than 2 percent of the total amount pumped. Hydraulic conductivity of the unit was not separately determined by straddle tests; however, Craig and Robison (1984) concluded that the 41 m of saturated Calico Hills penetrated by UE-25p#1 has a transmissivity of about 0.5 m^2/day. In contrasts in drillhole UE-25b#1, the tuffaceous beds of Calico Hills yielded 32 percent of the production (Figure 3-38) during pumping of the entire hole (Lahoud et al., 1984). In the vicinity of UE-25b#1, the unit is zeolitized and would have low matrix hydraulic conductivity; therefore, the relatively high values determined from in situ tests (Table 3-27) probably are due to nearby normal faults or shear fractures (Waddell et al., 1984).

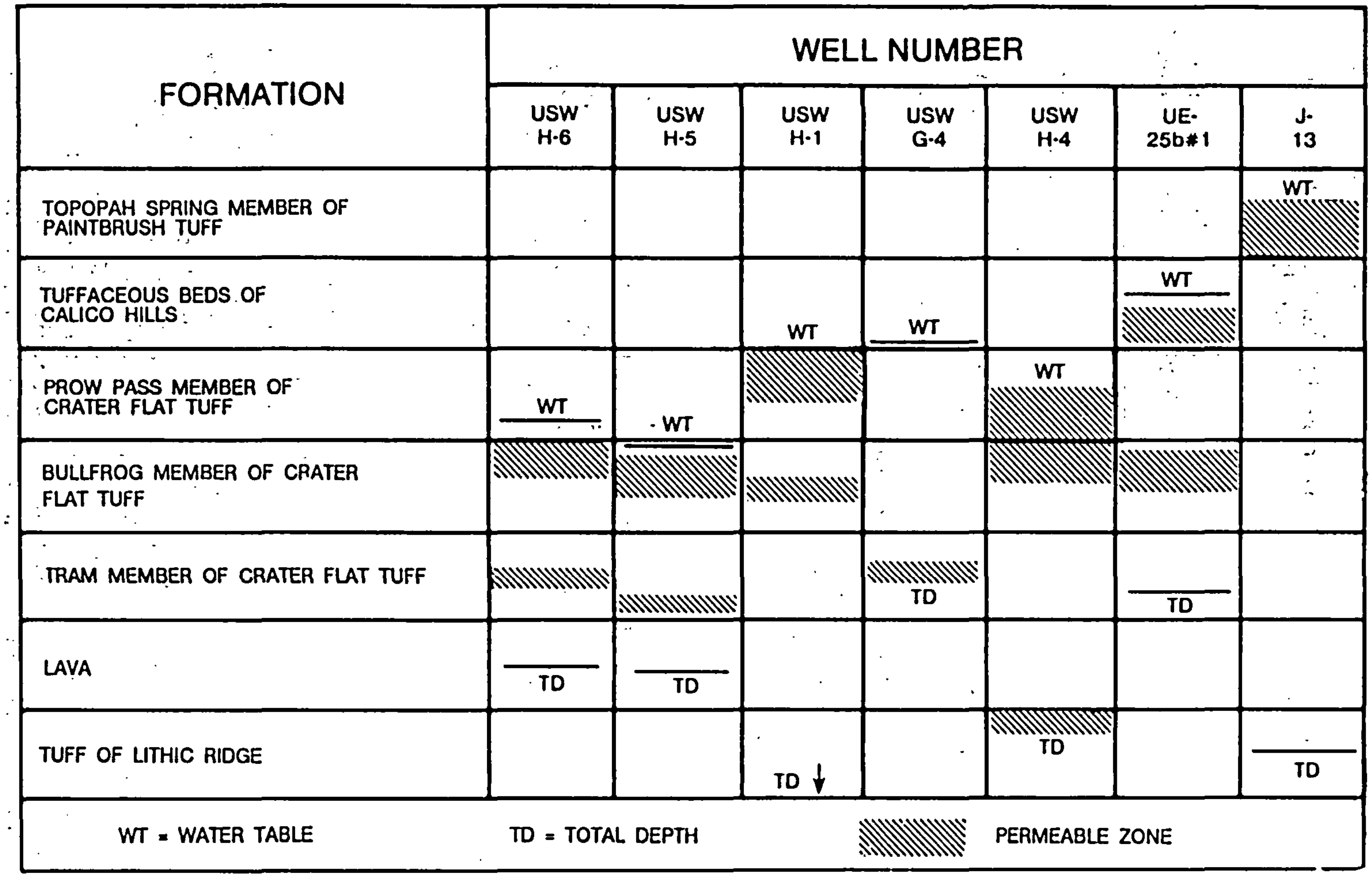


Figure 3-39. Vertical distribution of permeable zones in selected wells in the Yucca Mountain area. Modified from Benson et al. (1983).

The Prow Pass and Bullfrog members of the Crater Flat Tuff are generally similar in hydrologic properties and are commonly the most productive ones penetrated by drillholes in the vicinity of Yucca Mountain (Figures 3-38 and 3-39). Their in situ bulk hydraulic conductivity is controlled largely by fractures (Waddell et al., 1984). Results from in situ tests and core analyses for drillhole USW H-1 are shown in Table 3-29 (Rush et al., 1984).

The Tram Member of the Crater Flat Tuff generally is much less permeable than any of the overlying saturated units; at drill hole UE-25b#1, for example, the Tram yielded no measurable production during pumping of the entire hole (Figure 3-38; Lahoud et al., 1984). An exception occurs at drill hole USW G-4, where about 98 percent of the water production was from the Tram Member, although the overlying Bullfrog and Prow Pass Members are saturated; yield probably is from shear fractures noted in the lithologic log (Bentley, 1984). Table 3-27 shows that hydraulic conductivity for the Tram Member is as low as 7×10^{-6} m/d (drillhole USW H-1), and as high as 0.2 to 0.8 m/d (drillhole USW H-4).

Hydraulic conductivity of Tertiary rocks older than the Crater Flat Tuff ranges from about 2×10^{-6} to 3×10^{-2} m/d (Table 3-27).

Pre-Tertiary age rocks have been penetrated in only one drillhole in the vicinity of Yucca Mountain, at drillhole UE-25p#1 (Figures 3-28 and 3-25), where Paleozoic carbonate rocks of the Lone Mountain Dolomite and Roberts Mountains Formation were observed (Craig and Robison, 1984). They reported an average hydraulic conductivity value of 0.2 m/day.

3.9.2.2.3 Porosity and storage coefficients

Laboratory results of total porosity of cores ranging from 4 to 34 percent are shown in Table 3-27 and discussed in Chapter 2. Porosities reported by Anderson (1981) and by Thordarson (1983) were determined by water-saturation techniques, as described by Anderson (1981). The values reported for Lahoud et al. (1984) and Rush et al. (1984) were calculated by helium pyncnometer; they reported generally similar values for porosity calculated from dry-bulk and grain densities.

Waddell (1984) estimated effective porosity between two drill sites to be on the order of 1×10^{-4} to 1×10^{-3}, based on breakthrough of a tracer placed in drillhole UE-25a#1 while drillhole UE-25b#1 was being pumped.

Using a method that involves calculating equivalent fracture apertures, Erickson and Waddell (1985) determined that fracture porosity at drillhole USW H-4 is 1×10^{-4} to 1×10^{-3}. They concluded that, if most water moves through fractures rather than the rock matrix, fracture porosity approximates effective porosity. Although results from single-hole tests are not necessarily reliable, Rush et al. (1984) used slug-injection tests to estimate storage coefficients that range from 2×10^{-3} to 6×10^{-6} among the stratigraphic units penetrated at drillhole USW H-1. Using the same data from drillhole USW H-1, Barr (1985) calculated values for storativity (storage coefficient) that are about an order of magnitude lower.

Various hydraulic tests are being performed in the vicinity of drill-holes UE-25c#1, UE-25c#2, and UE-25c#3 to obtain more values for effective porosity and storage coefficients that will give a range of values that may be expected in the vicinity of the Yucca Mountain site (Section 8.3.1.2.3.1).

3.9.3 GROUND-WATER FLOW SYSTEM CONCEPTUAL MODEL

As indicated in the remarks prefacing Section 3.9, a conceptual model of a ground-water flow system uses available hydrogeologic data for the system to synthesize a general understanding of the overall (macroscopic) hydrologic system in terms of the specific (microscopic) hydrologic processes that are expected to operate within it. The macroscopic elements of the conceptual model include the hydrogeologic framework, a set of hydrologic boundary conditions (including the direction and magnitude of moisture or ground-water flux across the boundaries), and a knowledge of the present (initial) hydrologic state of the system, that is, the spatial distribution of hydraulic head in the saturated zone and of matric potential or saturation in the unsaturated zone. The microscopic elements are supplied by or developed from the fundamental concepts describing liquid and gaseous flow and storage in permeable media. Because it is usually abstracted from an incomplete set of data, a conceptual model generally consists of a collection of hypotheses that must be tested not only against existing data but also continually against new data as they become available. Consequently, one principal utility of a conceptual model is to guide data collection to permit adequate testing and evaluation of hypotheses. The hypotheses, thus, may be accepted, rejected, refined, or replaced by alternatives in the light of new data and improved understanding of the flow system.

The unsaturated zone beneath Yucca Mountain consists of a stratified block of east-dipping hydrogeologic units composed of welded and nonwelded tuffs of contrasting hydraulic properties. Some of these units are highly fractured, and the fractures may either enhance or retard the flow of moisture. The Yucca Mountain block contains and is bounded by west-dipping high-angle normal faults that, depending on location and ambient hydrologic conditions, may be pathways for or barriers to moisture flow. The mechanisms of moisture flow and storage (as liquid water, water vapor, or both) at any location within the system depend on the amount of water entering the system as net infiltration. The actual rate and distribution of net infiltration over the surface of Yucca Mountain is not presently known, although likely upper bounds have been established.

Generalized conceptual models for moisture flow within the unsaturated zone beneath Yucca Mountain have been developed by Montazer and Wilson (1984) and Sinnock et al. (1986). In addition, specific hydraulic problems were conceptualized by these authors, Klavetter and Peters (1986), and Wang and Narasimhan (1985, 1986). The essential features of these models define the hydrogeologic framework and identify the possible processes of moisture flow and storage that occur under the constraints imposed by the hydrogeologic framework. One conceptual model is illustrated schematically in Figure 3-40, which depicts a generalized east-west cross section through Yucca Mountain. The hydrogeologic framework consists of the eastward-tilted Yucca Mountain block, composed of the stratified sequence of hydrogeologic units listed in

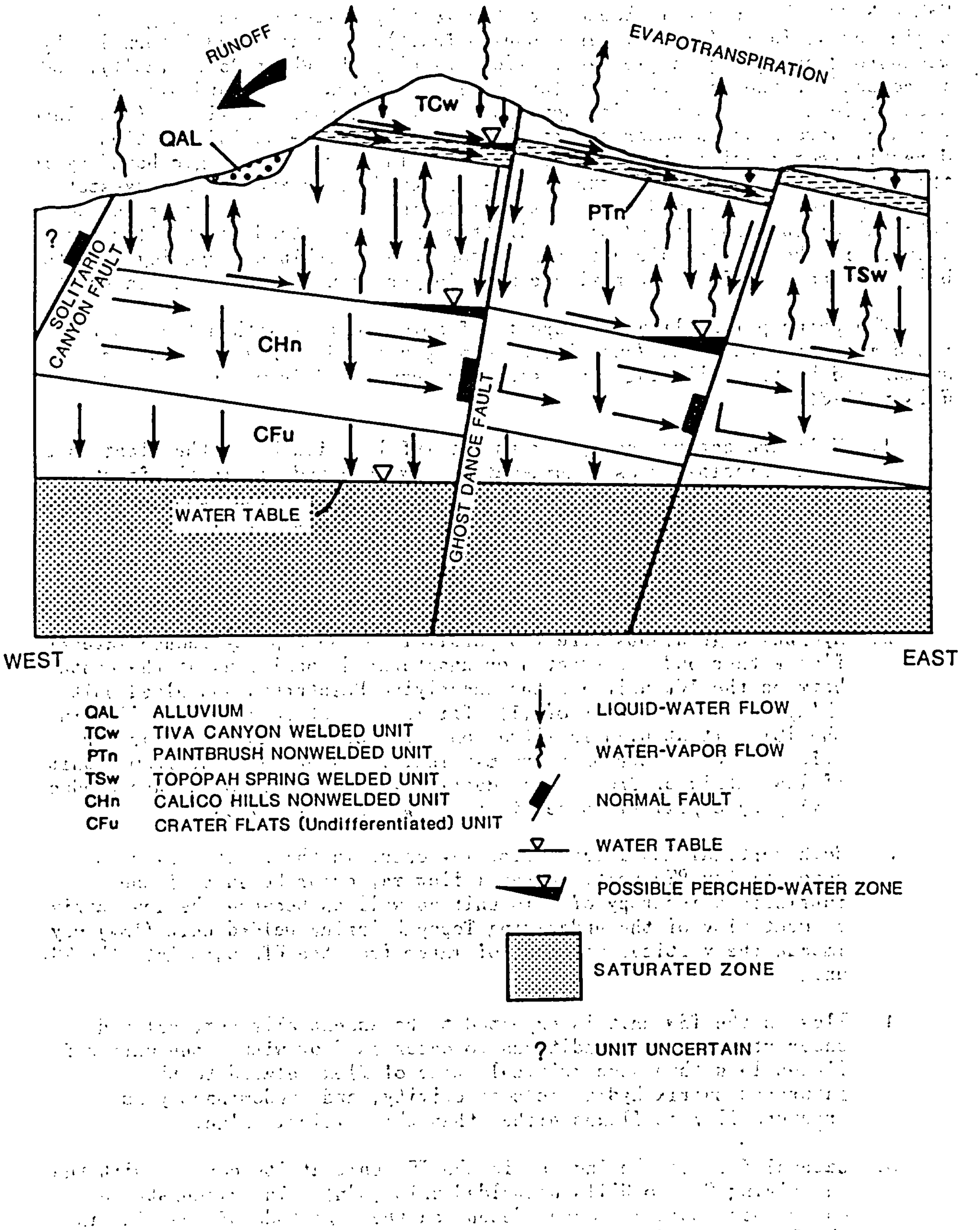


Figure 3-40. Generalized east-west section through Yucca Mountain showing conceptual moisture-flow system under natural conditions. Modified from Montazer and Wilson (1984).

Table 3-22. The block is bounded on the west by a westward-dipping high-angle normal fault (the Solitario Canyon fault), is transected internally by westward-dipping high-angle faults (for example, the Ghost Dance fault), and is bounded on the east by a set (or zone) of imbricate westward-dipping high-angle normal faults. The upper hydrologic boundary consists of the land surface, across which water enters the unsaturated zone as infiltration directly from precipitation or from runoff. The lower hydrologic boundary is the water table, whose configuration is presumed to be known. Steady-state moisture flow is presumed to be established in all but a thin, near-surface interval of the unsaturated zone. In this instance, steady-state flow may be assumed if the time required to change conditions within hydrogeologic units below the near-surface interval are much longer than the period of interest.

The principal qualitative aspects of moisture flow within the unsaturated zone beneath Yucca Mountain, as conceptualized in Figure 3-40, are summarized by the following hypotheses, as summarized from Montazer and Wilson (1984):

1. Moisture enters the system as net infiltration below the plant-root zone principally as liquid-water flow into and within the fractures of the surficial Tiva Canyon welded unit (TCw) with subsequent uptake under capillary forces into the TCw matrix. It is expected that at sufficiently low rates of net infiltration, all the water entering the TCw unit may be drawn into the matrix before the full thickness of the TCw unit is traversed.

2. Hydraulic gradients directed parallel to the dip may induce lateral flow either under saturated or unsaturated conditions at the contact between the TCw unit and the underlying Paintbrush nonwelded unit (PTn) as a consequence of (1) efficient fracture-dominated flow in the TCw unit at high infiltration rates or (2) capillary barrier effects. Capillary barriers may inhibit water movement from a unit of low matrix or fracture conductivity into a unit of higher conductivity by capillary forces in the low-conductivity unit.

3. Both vertical and lateral flow may occur in the relatively high-conductivity PTn unit. Lateral flow may occur because of the intrinsic anisotropy of this unit as well as because the low matrix conductivity of the underlying Topopah Spring welded unit (TSw) may impede the vertical movement of water from the PTn unit into the TSw unit.

4. Flow in the TSw unit is expected to be essentially vertical and under steady-state conditions to occur as flow within the matrix for fluxes less than some critical value of flux related to the saturated matrix hydraulic conductivity, and predominantly as fracture flow at fluxes higher than the critical value.

5. Lateral flow may be induced in the TSw unit at its contact with the underlying Calico Hills nonwelded unit (CHn). The circumstances under which this may occur depend on the magnitude of the flux in the TSw unit and whether this unit is underlain by the low-conductivity zeolitic facies (CHnz) or the relatively higher-conductivity vitric facies (CHnv) of the CHn unit. At low fluxes

within the TSw unit, lateral flow may be produced by capillary-barrier effects within the matrix of the TSw unit where it overlies the CHnv unit. At high fluxes, efficient fracture flow in the TSw unit may produce lateral flow as well as vertical flow where the low-conductivity CHn unit underlies the TSw unit.

6. Flow in both the CHnv and CHnz units is predominantly vertically through the matrix (although a lateral component may occur parallel to the bedding within the vitric CHnv unit) and continues directly to the water table wherever the latter transects the CHn unit. Where the CHn unit lies above the water table, flow is presumed to proceed vertically downward to the water table through the Crater Flat undifferentiated unit (CFu).

7. The nearly vertically oriented fault zones and their associated fracturing may be highly effective pathways for vertical moisture flow, especially in the competent TCw and TSw units. But faults may impede lateral flow and may thus produce perched-water bodies where the faults transect zones or horizons of significant lateral flow.

8. Temperature-driven moisture transport may occur, especially within the highly fractured TSw unit. This could be expected to occur by molecular diffusion if local thermodynamic phase equilibrium is maintained between liquid water and water vapor within the system, which would produce a water-vapor concentration gradient along the natural geothermal gradient. Of greater importance may be the advective transport of water vapor accompanying thermally or barometrically driven upward bulk-gas flow within the fractures of the TSw unit. Under steady-state conditions, the upward movement of water vapor in the air-filled fracture openings would be compensated by downward return flow of liquid water within the rock matrix.

9. Moisture flow within the deep unsaturated zone at Yucca Mountain may be occurring under essentially steady-state conditions. The steady-state hypothesis implies that moisture flow within the natural system is occurring predominantly as vertically downward liquid-water flow within the rock matrix of the hydrogeologic units with possible water-vapor movement within the air-filled pore and fracture space. Significant liquid-water flow within the fractures may occur but only as near-surface, transient, nonequilibrium events that are followed by eventual uptake by the rock matrix of water descending through the fractures. Equilibrium would prevail between the liquid-water matric potentials in the fractures and the unsaturated rock matrix at depth. Liquid water movement could occur in fractures as well as the matrix. Although the amount of fracture flow probably would be small, additional understanding of the factors controlling fracture flow is needed to assess this phenomenon. Under these conditions, the liquid-water flux through the matrix of the TSw unit would be expected to be less than the mean matrix saturated hydraulic conductivity of about 1 mm/yr, as determined for this unit by Peters et. al. (1984).

This set of qualitative hypotheses is evaluated in terms of presently available data and uncertainties in Section 3.9.3.4, unsaturated zone relationships.

A general geohydrologic conceptual model for saturated ground-water flow near Yucca Mountain is based upon division of the Tertiary stratigraphic units into (1) moderately and densely welded tuff and (2) nonwelded and bedded tuffs, as a result of the different hydrologic properties of these materials. The moderately and densely welded tuffs are characterized by relatively low porosities, abundant fractures, and low matrix permeability. In nonwelded and bedded tuffs, porosities are greater and fractures are fewer, although fractures do occur. Unless the rock contains clays or zeolites, matrix conductivities are generally larger than in the welded tuffs (Waddell et al., 1984).

This model provides a basis for predicting saturated hydraulic properties near Yucca Mountain, provided that the welding characteristics and extent of secondary mineralization of units are known. The Paintbrush Tuff is mostly unsaturated; the Topopah Spring Member, which is unsaturated in the repository block, but saturated east of Yucca Mountain (Figures 3-28 and 3-25), consists mostly of moderately to densely welded tuffs. The Crater Flat Tuff (Prow Pass, Bullfrog, and Tram members) consists of partially to moderately welded tuffs. The tuffaceous beds of Calico Hills and Lithic Ridge Tuff are predominantly nonwelded and bedded tuffs. In addition, bedded tuffs commonly separate the major ash-flow tuff units.

Partial alteration of vitric tuffs to zeolites or clays reduces their permeability substantially. Thickness of the zeolitic facies of the tuffaceous beds of Calico Hills increases from southwest to northeast (Figure 3-41), and the entire unit is altered beneath the northern and northeastern parts of the Yucca Mountain repository block (Montazer and Wilson, 1984) (see Section 3.9.2.1).

All the Tertiary stratigraphic units just discussed are within the regional "tuff aquitard" considered by Winograd and Thordarson (1975). Beneath Yucca Mountain are Paleozoic carbonate rocks, equivalent to the regional "lower carbonate aquifer" of Winograd and Thordarson (1975). These rocks occur at a depth of 1,200 m in drill hole UE-25p#1 and probably much deeper elsewhere (Craig and Robison, 1984). These carbonate rocks are permeable, but at Yucca Mountain the potentiometric head, as measured at drill hole UE-25p#1 (which is the only drillhole penetrating the Paleozoic rocks), is greater in the Paleozoic rocks than in overlying rocks. These rocks, in ascending order include Lithic Ridge Tuff and other tuffs of low permeability, Crater Flat Tuff, and Paintbrush Tuff (Craig and Robison, 1984; Robison, 1984). Therefore, ground water moving through the shallow part of the saturated zone in the vicinity of the Yucca Mountain repository block probably does not have significant local interaction with water from the Paleozoic rocks.

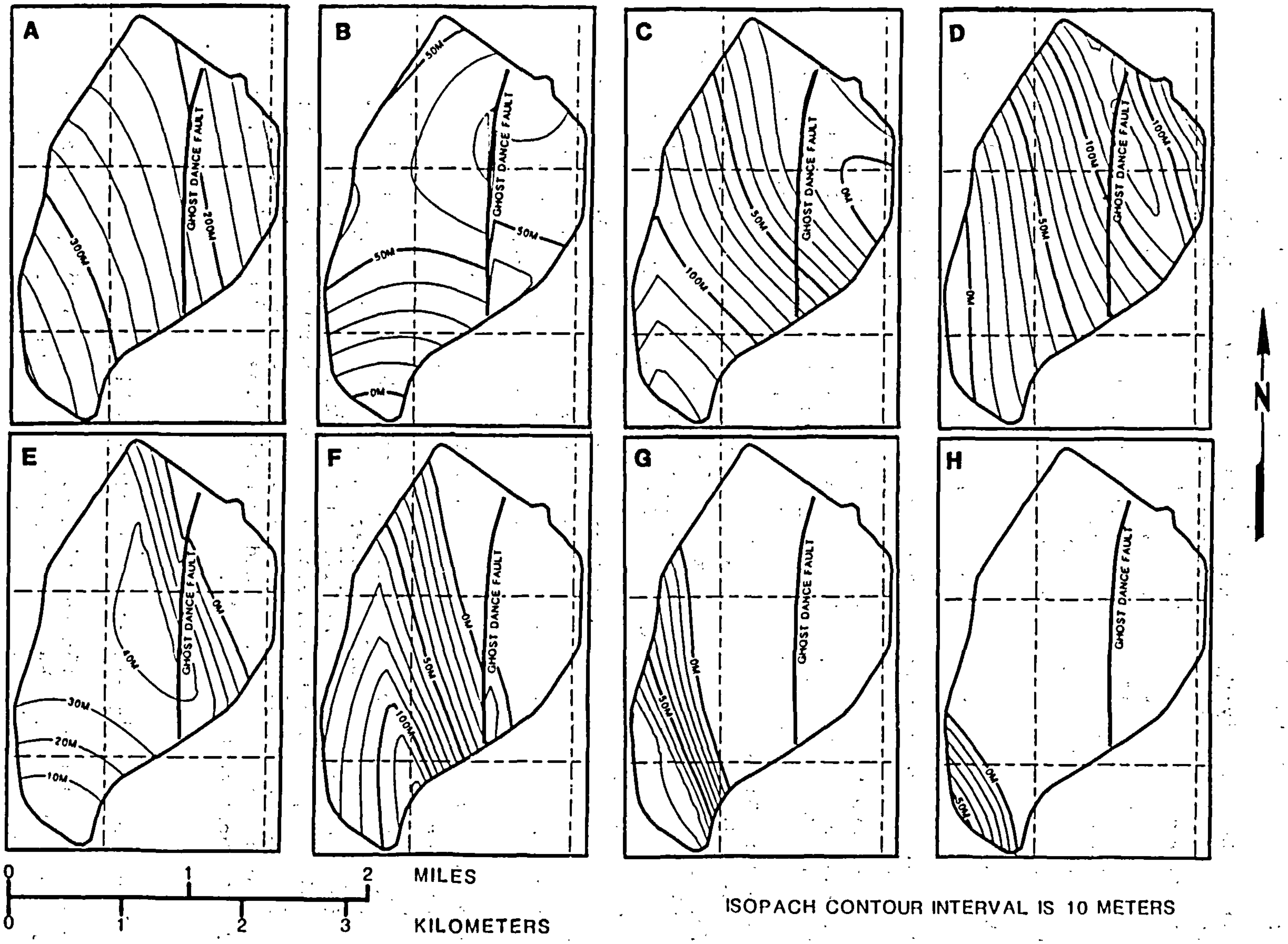


Figure 3-41. Isopach contour maps within the repository block: (A) Total thickness from disturbed zone to the water table; (B) Thickness of undisturbed Topopah Spring welded unit TSw; (C) Thickness of the Calico Hills nonwelded vitric unit, CHnv; (D) Thickness of the Calico Hills nonwelded zeolitic unit CHnz; (E) Thickness of the Prow Pass welded unit, PPw; (F) Thickness of the Prow Pass nonwelded unit, PPn; (G) Thickness of the Bullfrog welded unit. Modified from Sinnock et al. (1986).

3.9.3.1 Accessible environment and credible pathways

The proposed repository horizon at Yucca Mountain is within the unsaturated TSw unit, about 250 m above the water table and ranging from about 80 m to 140 m above the underlying CHn unit. The most credible pathway for liquid-water movement from the repository horizon enroute to the accessible environment depends to a large extent on the flow mechanisms with the TSw unit. These, in turn, depend on the saturation as well as on the flux and its time rate of change. If the matrix and fracture saturation are sufficiently low, liquid-water movement is expected to be restricted to the matrix of the TSw unit and will tend to be directed vertically downward continuing through the CHn unit to the water table.

In the unsaturated zone, matrix saturations within the fractures of the TSw unit may exceed some critical values and cause significant liquid-water flow. The fractures, depending on local conditions, may be capable of delivering relatively large volumes of water from the repository horizon rapidly to the contact between the TSw and CHn units. Adequate data are presently lacking to evaluate these hypotheses quantitatively. Ambient saturation within the TSw unit at the repository horizon is inferred, from data obtained from test wells USW H-1, USW UZ-1, and UZ-6, to be in the range 0.4 to 0.6 (Sections 3.9.2.1 and 3.9.3.4), and the vertical flux at this horizon has been estimated by Wilson (1985) to be 0.5 mm/yr or less. This value is less than the mean value for the saturated matrix hydraulic conductivity of about 1 mm/yr for the TSw unit (3×10^{-11} m/s in Table 3-26), and implies that the flux probably occurs principally in the matrix and not in fractures of the TSw unit. However, Montazer and Wilson (1984) indicate that fracture flow may occur at saturations less than 100 percent. In addition, according to Montazer and Wilson (1984), net infiltration may be considerably greater than the average flux in the TSw unit. Tests are planned to evaluate the conditions under which flow in fractures and faults may occur (Section 8.3.1.2.3), thus aiding in the definition of flow paths in the unsaturated zone.

In the saturated zone, differences in potentiometric levels indicate general directions of ground-water flow. In general, ground-water flow beneath Yucca Mountain probably is southward through the site, southeastward away from the site into the Fortymile Wash area. However, because of the nearly flat potentiometric surface under parts of Yucca Mountain, specific flowpath directions are currently difficult to define. Furthermore, the degree of anisotropy has not been evaluated. Additional water-table holes and extensive multiple-well and single-well tracer tests may help define anisotropy, hydraulic connections, and probable flow paths in the saturated zone (refer to Section 8.3.1.2.3.1).

3.9.3.2 Potentiometric levels and head relationships

This section discusses the relationships between matric potentials for hydrogeologic units within the unsaturated zone and between potentiometric levels for units within the saturated zone.

3.9.3.2.1 Unsaturated zone

Little direct information on matric potentials and moisture fluxes is presently available for the unsaturated zone beneath Yucca Mountain. Weeks and Wilson (1984) report the results of measuring ambient rock-matrix saturations on 19 samples from cores obtained in test well USW H-1 (Figure 3-28). The well was drilled using an air-foam detergent mixture as drilling fluid (Rush et al., 1983), which minimized possible moisture uptake by the core samples. Mercury intrusion techniques were used to develop moisture-retention curves for each of the samples from which ambient matric potentials were inferred. The resulting set of moisture-retention curves differs considerably from the analytic representations of Peters et al. (1984) shown in Figure 3-33, which were based on psychrometric measurements made over a range of matric potentials much less than the minimum value of about -0.20 MPa that could be measured by Weeks and Wilson (1984). Only one sample was available from the PTn hydrogeologic unit at a depth of 33.5 m below land surface; it had a matric potential of -0.15 MPa at an ambient saturation of 0.51. Sixteen samples were available for the TSw unit spanning a vertical interval of 278 m within the unit. The lowest saturation measured within this sample set was 0.47, the highest was 0.89, and the mean was 0.65. There was a poorly defined indication within the sample set for saturation to increase with depth. The matric potentials inferred from the measured saturations for the samples were highly variable, ranging from -0.07 to more than -0.25 MPa with a mean of -0.18 MPa and a standard deviation of -0.06 MPa. Two samples were available from the CHn unit at a depth of 530 m and both indicated complete matrix saturations. Because of the considerable scatter within the set of data, the matric-potential and saturation values for the samples from the TSw unit do not define a unique, representative moisture-retention curve for this unit. It is not known to what extent this scatter may be attributed to intrinsic heterogeneity of properties and conditions within the TSw unit or is due to undetermined experimental errors of measurement. Consequently, these data from drillhole USW H-1 probably are best interpreted as indications only of the hydrologic conditions that may be expected to be encountered within the hydrogeologic units of the unsaturated zone at Yucca Mountain.

As described in Section 3.9.1.1.1, test well USW UZ-1 (Figure 3-27) has been drilled to a total depth of 387 m within the unsaturated zone at Yucca Mountain and instrumented with thermocouple psychrometers and heat-dissipation probes to monitor in situ matric potentials at 33 selected depths within the TCw, PTn, and TSw hydrogeologic units (Montazer et al., 1985). Data from two years of continued monitoring indicate that hydrologic conditions within the borehole may be in approximate equilibrium with ambient conditions in the surrounding units. The data available to date are shown in Figures 3-30 and 3-31. Although the data show considerable variability, there is no well-defined systematic variation of matric potential with depth within hydrogeologic units, which is consistent with the supposition that the individual hydrogeologic units are relatively homogeneous in the vertical direction and that steady-state vertical moisture flow occurs under unit vertical hydraulic gradient. The trend with time, if interpreted as the approach to equilibrium between the well and its surroundings, indicates that present ambient matric potentials generally are greater than -1 MPa, and that the mean matric potential over the total depth of the borehole is about -0.3 MPa. These data from borehole USW UZ-1 are consistent with the range of values of matric potential inferred by Weeks and Wilson (1984) to be representative of conditions within the interval of the unsaturated zone penetrated by borehole USW H-1. As described in Section 8.3.1.2.2, additional test holes in the unsaturated zone will be drilled and instrumented to better define the distribution of matric potentials and fluxes.

3.9.3.2.2 Saturated zone

Measured head values used to construct the saturated-zone potentiometric map (Figure 3-28) are mostly composite heads, reflecting heads similar to those in the zones of higher transmissivity.

The hydraulic gradient is low in western Jackass Flats (Fortymile Wash area) and in the Amargosa Desert; the gradient is high in volcanic rocks north of Yucca Mountain and across northern Yucca Mountain. Low-permeability rocks likely occur where the gradients are steep, but the steep gradients may be caused by poorly-permeable faults. In areas where it may be important to know the cause of steep gradients, additional drilling or hydrologic testing is planned (Section 8.3.1.2.3).

Significant vertical hydraulic gradients have been observed in only a few drillholes: in drillhole UE-25p#1, the head in Paleozoic carbonate rocks that occur below a depth of 1.2 km is about 19 m higher than in the shallow zone; in drillhole USW H-1 the head is about 54 m higher in the older tuffs of Tertiary age, at a depth of 1.8 km; and preliminary data from drillhole USW H-3 suggest that the head below 0.8 km (Tram Member of Crater Flat Tuff) is about 40 m higher. These higher heads occur only within or below intervals of low permeability. Semipermanent packers are installed in lower sections of several drillholes (UE-25b#1, USW H-3, USW H-4, USW H-5, and USW H-6) to enable comparison of water levels above and below the packers. Except in drillhole USW H-3, vertical differences of head within the Paintbrush and Crater Flat tuffs have been less than a meter.

The upward component of ground-water flow that is indicated by higher heads in the deeper part of the saturated zone may be the result of the position of Yucca Mountain within the regional ground-water flow system. Simple models of ground-water basins consist of an area where recharge occurs (vertical flow is downward), and where discharge occurs (vertical flow is upward). In intermediate areas, flow is transitional from downward, to strictly horizontal, to upward (Figure 3-42). Although the Alkali Flat-Furnace Creek Ranch subbasin (of which Yucca Mountain is a part) is not simple, these concepts generally apply. Thus, Yucca Mountain is in an area where local vertical flow may be either up or down (Waddell et al., 1984). Erickson and Waddell (1985) observed slight upward and downward movement among different intervals of the same drillhole (USW H-4). This upward and downward movement may also be due to differences in horizontal and vertical hydraulic conductivity beneath Yucca Mountain.

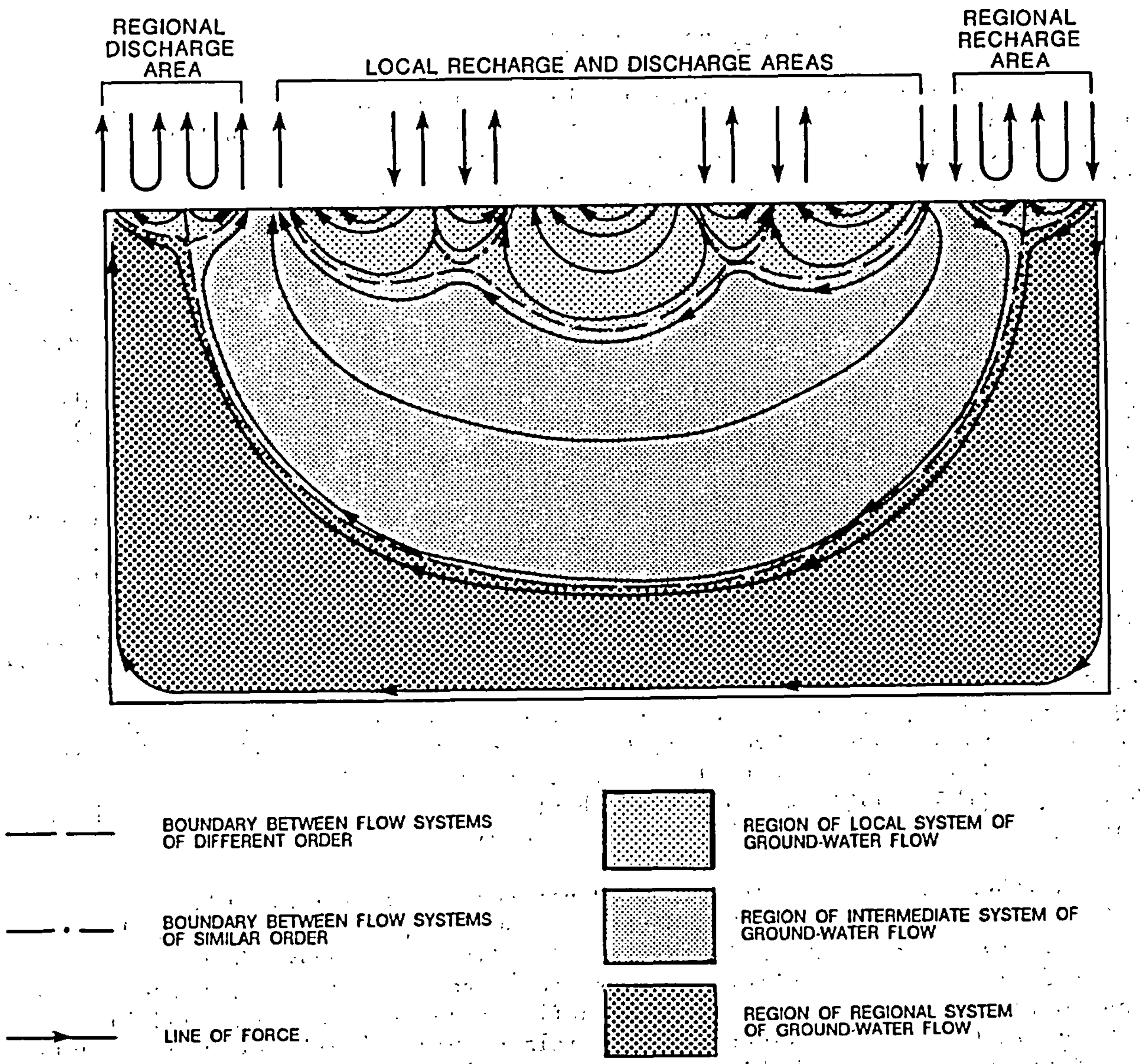


Figure 3-42. Standard theoretical flow pattern and boundaries between different flow systems. Modified from Toth (1963).

3.9.3.3 Recharge-discharge and leakage

The ultimate source of moisture in the unsaturated zone at Yucca Mountain is by net infiltration from precipitation on the mountain, and the quantity of precipitation is used by some techniques to estimate net infiltration and, subsequently, recharge. Net infiltration refers to the rate and quantity of water entering the unsaturated zone below the plant-root zone and represents moisture that is effectively inaccessible for direct return to the atmosphere by evapotranspiration. Recharge is the rate and quantity of water entering the saturated zone from the unsaturated zone (the term specifically excludes underflow into or out of the region of interest; recharge to adjacent areas subsequently may enter the region of interest as underflow). Direct measurements of precipitation at Yucca Mountain have been initiated, but too recently to provide reliable annual average values (Section 5.1). However, precipitation at the site has been estimated from the regional distribution of precipitation or from relationships established between altitude and precipitation. From a regional map of precipitation presented by Winograd and Thordarson (1975), precipitation at Yucca Mountain is estimated to be about 100 to 150 mm/yr (Section 5.1). Quiring (1983) established local relationships between altitude and precipitation for 1964-81 at the NTS. Quiring's (1983) data included limited data outside the NTS and data from 13 stations within the NTS that range in altitude from 3,000 to 7,490 ft (914 to 2,283 m). From a map showing precipitation-to-altitude ratios (Quiring, 1983), precipitation for the approximate range of altitudes at Yucca Mountain (about 1,220 to 1,465 m) is estimated to be 138 to 166 mm/yr, or an areal average of about 150 mm/yr (Montazer and Wilson, 1984). Quiring's (1983) data indicate that about 73 percent of this quantity falls during October through April (Montazer and Wilson, 1984).

Neither the spatial distribution nor the temporal variation of net infiltration is known at Yucca Mountain. However, an intensive field and experimental investigation of this process has been planned (Section 8.3.1.2.1). Spatial variations of net infiltration are mostly dependent on the variations in properties of the surficial units, topography and the vegetative cover. The surficial materials consist of alluvial and colluvial deposits and fractured welded tuffs, principally the Tiva Canyon welded unit. The area underlain by outcrops of nonwelded units is small. Alluvial and colluvial deposits fill the valleys and washes that form the main channels for surface runoff. The Tiva Canyon welded unit crops out throughout most of the repository block, and this unit has the most exposure to precipitation (Montazer and Wilson, 1984). Vegetation is sparse and consists mostly of xerophytes that delimit the depth of the plant-root zone.

Because of the great thickness of the unsaturated zone, the temporal variation and spatial distribution of recharge beneath Yucca Mountain are not expected to be equal to the temporal variation and surficial distribution of net infiltration. Temporal variations of net infiltration are expected to be damped rapidly with depth in the uppermost few tens of meters of the unsaturated zone (Weeks and Wilson, 1984) to produce approximately steady-state moisture flow at greater depths. Slow temporal variation of the moisture flux at any horizon is expected to occur generally only in response to long-term climatic changes. The spatial distribution of recharge beneath Yucca Mountain depends complexly on the hydrogeologic framework, the hydrologic properties, and the flow processes within the unsaturated zone and is not amenable to direct determination. Because the ground-water travel time through the unsaturated zone is likely to be of the order of several tens of thousands of years and because precipitation is decreasing regionally (Section 5.2.1), the present rate of net infiltration at Yucca Mountain probably is somewhat less than the present rate of recharge. Consequently, the present rate of net infiltration over the surface of Yucca Mountain probably is not a reliable indicator of either the net recharge beneath Yucca Mountain nor the net moisture flux, at or below the repository horizon.

Recharge to the saturated zone and the deep aquifers has been estimated within the region surrounding Yucca Mountain. For example, recharge to the regional carbonate aquifer, which underlies much of the NTS and vicinity, was estimated to be 3 percent of the precipitation falling on upland outcrops of this aquifer on the basis of measured spring discharge at Ash Meadows (Winograd and Thordarson, 1975). Applying this percentage to average precipitation at Yucca Mountain (150 mm/yr) would imply a recharge rate of about 4.5 mm/yr. In addition, Waddell et al. (1984), using data from Winograd (1981), estimated a moisture flux of about 0.5 mm/yr through the alluvium in Yucca Flat, which, however, being 40 km northeast of Yucca Mountain, probably is not typical of the Yucca Mountain site. Also, Case et al. (1984) determined a typical value of pore velocity of "about one-third centimeter per year" (under unsaturated conditions) in Frenchman Flat, 40 km east of Yucca Mountain. This is equivalent to a flux of 1 mm/yr if an effective porosity of 30 percent is assumed for the soil at Frenchman Flat. None of these studies provides a reliable basis for estimating recharge at Yucca Mountain. As at all sites, the actual value of recharge at Yucca Mountain depends on site-specific, local microclimatic, soil, vegetative, topographic, and hydrogeologic conditions.

Methods for estimating recharge for ground-water basins in Nevada were developed by Maxey and Eakin (1949) and refined by Eakin et al. (1951) and Malmberg and Eakin (1962). The resulting Maxey-Eakin method uses regional relationships among recharge, altitude zones, and precipitation but it does not account for a number of factors, such as runoff during intense storms, local rainfall distribution, temperature, and vegetative cover. Rush (1970) used the method to estimate recharge in the vicinity of the NTS; Czarnecki (1985) used Rush's estimates as a basis for input to a two-dimensional ground-water flow model to simulate present hydrologic conditions over an area whose boundaries are approximately the same as the Alkali Flat-Furnace Creek Ranch subbasin of Waddell (1982). Czarnecki (1985) used Rush's (1970) results and estimated recharge to be about 0.5 mm/yr in a precipitation zone that includes Yucca Mountain as well as parts of Jackass Flats and Crater Flat.

Geothermal heat flux can be used for indirect estimation of ground-water percolation rates, where the conductive and convective components of the heat flux can be separated (Sass et al., 1980). Sass and Lachenbruch (1982) estimated a vertical water flux of 1 to 10 mm/yr in wells near Yucca Mountain that are deeper than 1 km. The geothermal method can only be expected to yield percolation or recharge values within an order of magnitude because, among other reasons, it assumes one-dimensional ground-water flow, without accounting for lateral flow. Montazer et al. (1985) used the method developed by Bredehoeft and Papadopulos (1965) to calculate the water flux in the unsaturated zone. Montazer et al. (1985) estimated 0.02 to 0.05 mm/yr of upward flux in the TSw unit.

No springs exist near Yucca Mountain, and no discharge from the saturated ground-water system occurs by evapotranspiration because the water table, which is 300 to 750 m below land surface (Robison, 1986), is much too deep to be affected.

Wilson (1985) reviewed available site and regional hydrogeologic data in order to set conservative upper limits on the present, net vertically downward moisture flux below the repository horizon at Yucca Mountain and on the present rate of net recharge to the saturated zone in the vicinity of Yucca Mountain. Wilson (1985) concludes (1) that the liquid-water percolation flux, directed vertically downward in the matrix of the TSw unit below the repository horizon, probably is less than 0.2 mm/yr, and (2) that the areally averaged rate of net recharge to the saturated zone in the vicinity of Yucca Mountain probably is less than 0.5 mm/yr. Although Wilson (1985) considered a number of processes, such as upward water-vapor flow in the fractures of the TSw unit at the repository horizon, these upper bounds on percolation and recharge fluxes must be regarded as preliminary estimates that have as-yet-unknown limits of uncertainty. These estimates are expected to be refined using data obtained from borehole monitoring of ambient hydrologic conditions within the unsaturated zone, from the surface-based infiltration experiments, and from the in situ measurements and experiments within the exploratory shaft, described in Sections 8.3.1.2.1 and 8.3.1.2.2.

Ground-water flow modeling studies of the saturated zone at Yucca Mountain and vicinity have been conducted by Waddell (1982), Czarnecki and Waddell (1984), Rice (1984), and Czarnecki (1985). These two-dimensional models consider areal variation in hydrologic properties, but vertically combine the properties of hydrogeologic units. Results from a three-dimensional steady-state ground-water flow model (Sections 8.3.1.2 and 8.3.1.2.3) will be used to gain a better understanding of the flow system.

The regional model (18,000 km^2) of Waddell (1982), Figure 3-43, of which the Yucca Mountain area is only a small part, specified constant ground-water flux over a model basin in the vicinity of Pahranagat Valley and Pahrump Valley, and constant flux out of the basin at Furnace Creek Ranch in Death Valley. No-flow boundaries coincide approximately with the other boundaries of the regional ground-water basin (Figure 3-7). Constant-head nodes were used at Alkali Flat to simulate ground-water discharge. This model calculated vertically-integrated lateral fluxes of 0.04 to 0.2 m^2/d at or near the Yucca Mountain repository block, based on assumed transmissivities of about 7 m^2/d and 750 m^2/d. The model and the results of Rice (1984) are generally similar to those of Waddell (1982).

The subregional model of Czarnecki and Waddell (1984) (Figure 3-43), covering 6,000 km^2, is smaller than that of Waddell (1982). Specific fluxes into the flow system were applied along the northern boundary of Jackass Flats, along Rock Valley, the western edge of the Amargosa Desert, the western edge of Ash Meadows, and along Fortymile Canyon (Figure 3-44). Fluxes out of the system were simulated by specifying discharge at Alkali Flat (Franklin Lake Playa) and Furnace Creek Ranch. Other external boundaries were specified as no-flow. Hydraulic heads along the northern

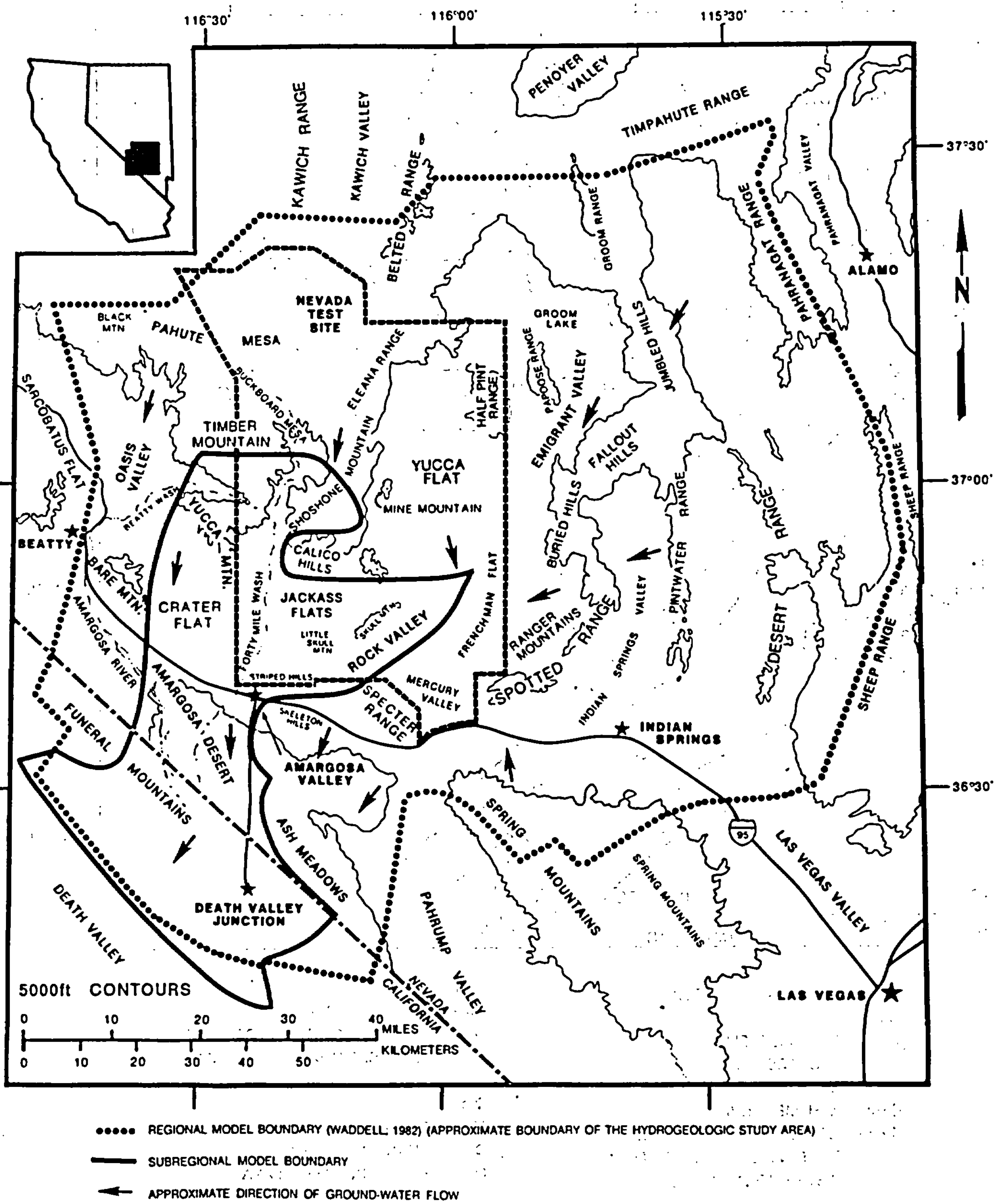
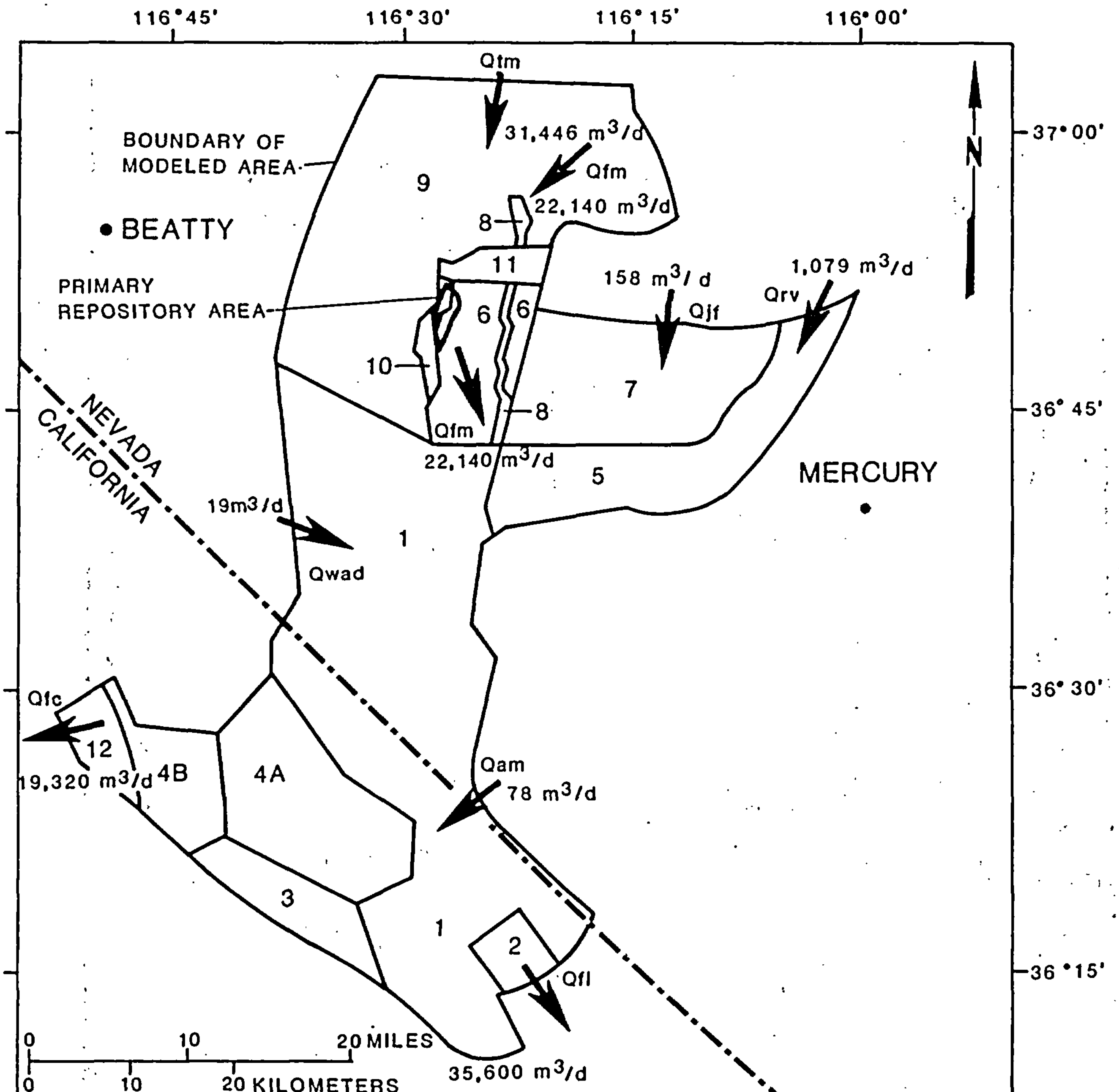


Figure 3-43. Location of regional and subregional modeled areas, with generalized ground-water flow directions. Modified from Czarnecki and Waddell (1984).



2	TRANSMISSIVITY ZONE	Qtm →	RESIDUAL FLUX
Qjf →	SPECIFIED FLUX	Qtm	TIMBER MOUNTAIN, CALCULATED AS A RESIDUAL OF THE MASS BALANCE
Qjf	JACKASS FLATS	Qfc →	DISCHARGE
Qrv	ROCK VALLEY	Qfc	FURNACE CREEK
Qam	ASH MEADOWS	Qfl	FRANKLIN LAKE PLAYA
Qwad	WESTERN AMARGOSA DESERT		
Qfm	FORTYMILE WASH (AREALLY DISTRIBUTED OVER ZONE 8)		

Figure 3-44. Locations and estimates of ground-water flow into and out of the Alkali Flat-Furnace Creek Ranch subbasin. Modified from Czarnecki and Waddell (1984).

boundary, near Timber Mountain, were specified as constant. Vectors of simulated vertically-integrated ground-water flux vary in direction from southeast to south, through and away from the Yucca Mountain repository block, and have a magnitude of about 2 to 3 m^2/d. These model-derived fluxes result from a parameter-estimation approach, in which an estimated transmissivity of 3,340 m^2/d was applied; although this value of transmissivity is somewhat greater than obtained from pumping tests, it is not outside the expected range of agreement.

3.9.3.4 Unsaturated-zone relationships

The factors controlling land-surface infiltration and the subsequent delivery of net infiltration as recharge to the water table are discussed in Section 3.9.3.3. The spatial distribution of net infiltration is one factor that controls moisture fluxes within the deep unsaturated zone beneath Yucca Mountain. No direct measurements of net infiltration have been made at Yucca Mountain and thus neither its magnitude nor its spatial and temporal distribution over the surface of Yucca Mountain are known. Montazer and Wilson (1984) estimate that the present average rate of net infiltration over the Yucca Mountain block may be expected to range from about 0.5 to no more than 4.5 mm/yr. As discussed in Section 3.9.3.3, Wilson (1985), in reviewing and analyzing available data, concluded that a value of 0.5 mm/yr may be a conservative upper bound for the mean vertical-downward percolation flux of water across the repository horizon. Net infiltration is expected to be episodic and unevenly distributed over the surface of Yucca Mountain. These irregularities, however, probably are smoothed rapidly with depth (Weeks and Wilson, 1984) so that the mean percolation rate at depth within Yucca Mountain is affected significantly only by large-scale climatic changes. If these changes occur sufficiently slowly in time, then the hydrologic system within the unsaturated zone can be presumed to adjust continuously to these changes so that an overall steady-state flow system may approximately exist at any point in time.

If, as is implied by the data obtained from test wells USW H-1, USW UZ-1, and USW UZ-6, the ambient liquid-water saturation within the repository TSw unit is within the range from about 0.5 to 0.7, then liquid-water percolation through the unit probably is matrix dominated (Klavetter and Peters, 1986; Peters et al., 1986) with little or no flow of water within fractures. Laboratory data (Table 3-26) indicate that the saturated hydraulic conductivity for the matrix of the TSw unit is about 3.5 x 10^{-11} m/s which, under a unit vertical hydraulic gradient, corresponds to a maximum vertical liquid-water flux through the matrix of about 0.8 mm/yr. At matrix saturations less than 1.0, this maximum flux within the TSw matrix would be reduced by the relative hydraulic conductivity appropriate to the matrix pore geometry and the ambient saturation. The relation between relative hydraulic conductivity and saturation for the TSw unit matrix material is not known. The van Genuchten (1980) representation used by Peters et al. (1984), however, would suggest a relative hydraulic conductivity factor of the order of 10^{-2} to 10^{-3} to be appropriate. Hence, the vertical percolation flux through the TSw unit, and by implication across the repository horizon within the unit, may well be about or much less than the 0.5 mm/yr maximum value estimated by Wilson (1985). This finding is consistent with the range of values from 0.1

to 0.5 mm/yr estimated by Montazer et al. (1985) from data obtained from borehole USW UZ-1 (Section 3.9.1.2.1). It must be emphasized that these analyses are very preliminary and approximate and presume that the TSw unit is laterally and vertically homogeneous and isotropic and that steady-state flow conditions prevail.

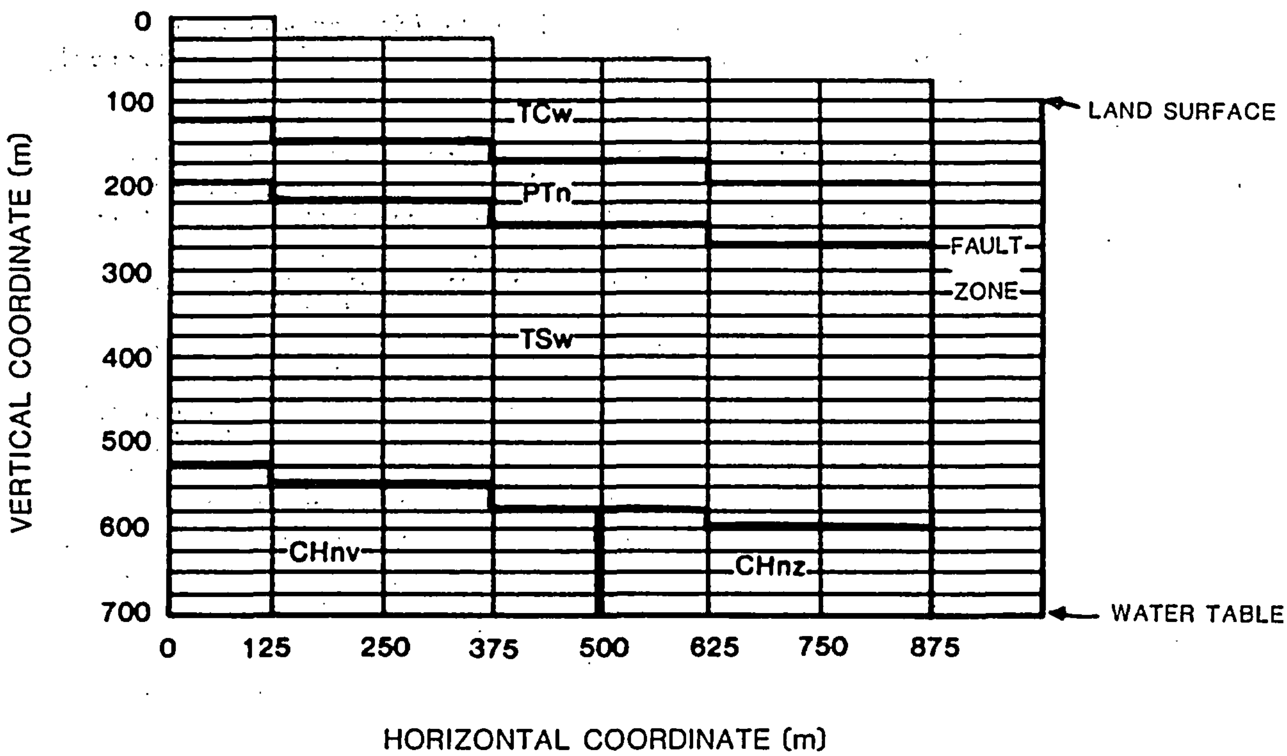
As described in Section 8.3.1.2.2, hydrologic data from the unsaturated zone at Yucca Mountain are to be obtained directly only from the exploratory shaft test facility and from a relatively small number of surface-based boreholes. Consequently, it will be necessary to rely on indirect methods, such as numerical flow and solute-transport modeling and geostatistical techniques, to infer the state of the presently existing natural hydrologic system by interpolating within and extrapolating from a somewhat incomplete set of field data (Section 8.3.1.2.2). Using data that are presently available for the site, several investigators have used these methods to perform rudimentary analyses and develop preliminary interpretations. These investigations have been directed in part towards examining some of the hypotheses underlying the conceptual model presented in Section 3.9.3 and contribute especially to identifying specific problems that will need to be resolved as part of the site-characterization program. These initial assessments, therefore, not only provide insight into the conceptualization of unsaturated-zone relationships at Yucca Mountain but also define specific data needs to be met by subsequent data acquisition at the site.

Peters et al. (1986) used a one-dimensional model to simulate liquid-water flow in an idealized but representative vertical column through the unsaturated zone at Yucca Mountain. They investigated the mode of liquid-water flow for a set of prescribed percolation fluxes within the column. The column was simulated to be 530.2 m in height and consisted of a basal CHnz or CHnv unit overlain by an upward succession of the units TSw, PTn, and TCw. The mean hydrologic properties for these units were taken from Peters et al. (1984). The results of these simulations indicate that virtually completely saturated conditions would be expected to occur within the TSw and TCw units for percolation fluxes exceeding about 0.5 mm/yr. This conclusion results from the values of the saturated matrix hydraulic conductivity for the TSw and TCw units that were used in the numerical simulations. The mean matrix conductivity values used for those two units were about 0.5 mm/yr. In a steady-state simulation, the value of percolation flux which induces saturated-matrix conditions in a particular hydrogeologic unit is directly proportional to its value of saturated matrix hydraulic conductivity. The results of the numerical simulations also predict that the time for the unsaturated system to return to steady state after a small change (a few tenths of a millimeter per year) in the steady percolation flux is on the order of tens or hundreds of thousands of years. These results suggest that the response time of the percolation flux at depth to changes in the net infiltration rate is very long. Greater percolation fluxes under this model would be expected to induce increasing volumes of flow within the fractures of the TSw and TCw units. However, the applicability of these results to Yucca Mountain is uncertain, because of (1) the limitations of one-dimensional modeling, which does not account for lateral heterogeneity, boundary conditions, and flow, and (2) the uncertainty in the representativeness of the hydrologic properties. None the less, these results, together with the moisture-content data from boreholes USW UZ-1, UZ-6, and H-1, which indicate that the rock matrix of the penetrated units is not saturated, support the empirically based estimates of Wilson (1985) and Montazer et al. (1985) that the average percolation flux within much of the TSw unit probably is less than about 0.5 mm/yr.

Sinnock et al. (1986) used one-dimensional modeling techniques to calculate probable ground-water travel times from the repository horizon to the water table (Section 3.9.4). These calculations assumed that steady-state moisture-flow conditions prevail within the unsaturated zone at Yucca Mountain and considered steady-state percolation fluxes of 0.1, 0.5, and 1.0 mm/yr. By varying flow-model parameters and using a Monte Carlo approach, probabilistic distributions for the ground-water travel time were developed. Although these calculations demonstrate the utility of the methodology, the quantitative results were sensitive to hydrologic-property input data that are as yet highly uncertain. Sinnock et al. (1986) emphasize the need for obtaining reliable field and laboratory hydrologic-property data for all of the hydrogeologic units that affect the travel-time calculations. In addition, they recommend that, to the extent that the sparse distribution of data-gathering sites will allow, geostatistical techniques be used to estimate the spatial correlation of hydrologic properties within and between hydrogeologic units. Geostatistical methods are also essential for the description of the unsaturated zone and the estimation of its hydraulic properties from the limited empirical data set that will be available from the Yucca Mountain site characterization studies.

Rulon et al. (1986) modeled multidimensional liquid-water flow within the unsaturated zone at Yucca Mountain by constructing a two-dimensional, vertical cross-sectional flow model to investigate: (1) the difference in steady-state flow patterns and moisture distributions that could result under the extremes of matrix-dominated or fracture-dominated liquid-water flow within the TCw and TSw units; and (2) the likelihood for the occurrence of down-dip lateral flow within hydrogeologic units or at the contacts between units in the presence of a highly-transmissive bounding fault-zone that could readily divert all lateral influx directly to the water table. The model numerically approximated the equations describing variably saturated ground-water flow within the unsaturated zone on the basis of the rectangular grid shown in Figure 3-45. The stair-stepping hydrogeologic-contact boundaries depicted in Figure 3-45 were introduced to simulate approximately the eastward dip of the hydrogeologic units within the Yucca Mountain block. The boundary conditions imposed on the model included a basal static water table, an upper land-surface infiltration boundary, and lateral boundaries consisting of a vertical impermeable boundary on the west and a highly transmissive vertical fault zone on the east. The bounding fault zone was introduced as an artifice to receive lateral flow from the units abutting the zone, however, the hydrologic characteristics of the vertical faults at Yucca Mountain are not known. Any correlation between this model and the system in place at Yucca Mountain may be premature. Further, any assumptions involving the effects of these faults on ground-water flow, travel times, etc., should be considered preliminary. Plans to investigate the hydrologic characteristics of the Ghost Dance Fault are presented 8.3.1.2.2.6.

Three sets of steady-state simulations were performed in which liquid-water flow was assumed to occur (1) as matrix flow in all of the hydrogeologic units, (2) only in the fractures of the TCw and TSw units but in the matrix of the other units, and (3) in either or both the matrix and the



TCw	TIVA CANYON WELDED UNIT
PTn	PAINTBRUSH NONWELDED UNIT
TSw	TOPOPAH SPRING WELDED UNIT
CHnv	CALICO HILLS NONWELDED VITRIC UNIT
CHnz	CALICO HILLS NONWELDED ZEOLITIC UNIT

Figure 3-45. Numerical grid used in the two-dimensional flow simulations. Modified from Rulon et al. (1986).

fractures of the TCw and TSw units. Constant values of land-surface net infiltration rate, spanning the range from 0.015 to 4.5 mm/yr, were used as parameters within each of the three sets of simulations.

Because the moisture-characteristic relations for each of the hydrogeologic units considered by Rulon et al. (1986) differed considerably from those used by Peters et al. (1984) for the same units, the steady-state vertical profiles of matric potential and saturation computed by Rulon et al. (1986) for a specified net-infiltration rate (or percolation flux) likewise differed quantitatively from those computed by Peters et al. (1984). Both sets of model calculations, however, predicted that steady net infiltration rates (or percolation fluxes) exceeding values in the range from 0.5 to 1.0 mm/yr would produce complete matrix saturation in the TSw and TCw units after the mountain equilibrates to the change in flux. These conditions could lead to liquid-water flow within the fractures of these units. Both sets of calculations are consistent with the hypothesis that the present net percolation flux in the TSw unit is less than about 0.5 mm/yr (Wilson, 1985; Montazer et al., 1985), and that the flux is transmitted predominantly within the rock matrix of the TSw unit under conditions of less than complete matrix saturation.

Although the representation depicted in Figure 3-45 of inclined hydrogeologic units abutting a vertical fault zone is crude, the model results of Rulon et al. (1986) suggest that there is the potential for significant lateral flow above the repository TSw unit. At a high rate of net infiltration (4.5 mm/yr), significant lateral flow was predicted to occur within fractures of the uppermost TCw unit. At lower infiltration rates, significant lateral diversion of vertical flux was predicted to occur within the high matrix-conductivity PTn unit above its contact with the underlying TSw unit. Because these model calculations, as well as those of Peters et al. (1986), are based on highly idealized representations of the physical system, use a coarse grid size, and use hydrologic-property data that are preliminary and with unknown limits of uncertainty, the model results may not be quantitatively reliable. One of the major tasks to be accomplished through the data-acquisition program at the site, as detailed in Section 8.3.1.2, is to collect sufficiently large sample sets to delimit the uncertainties associated with the quantitative predictions of the numerical models.

This discussion of the preliminary numerical models and their results presumes that natural moisture flow within the unsaturated zone at Yucca Mountain occurs solely as liquid-water movement through rock-matrix pores and fractures under isothermal, steady-state conditions. It will be difficult to assess the steady-state flow hypothesis during the short time span available to the site-characterization program. However, some indication of the degree to which steady-state flow is realized may be inferred from surface-based infiltration measurements and experiments (Section 8.3.1.2.1). If steady-state flow prevails, then the present rate and distribution of net infiltration over the surface of Yucca Mountain should be demonstrably consistent with the magnitude and distribution of moisture flux within the interior of the Yucca Mountain block, whether inferred from in situ measurements of hydrologic conditions or predicted through numerical simulations. Because of their expected low magnitudes, fluxes at depth probably will not be directly measurable within the unsaturated zone but will have to be inferred from measured potential distributions and hydrologic properties. In addition, numerical simulations may be needed to interpret these data and to estimate the limiting conditions under which these data support or refute the steady-state hypothesis. The analysis and interpretation of the Yucca Mountain hydrologic system will be complicated greatly if the steady-state approximation is invalid. The appropriateness of this approximation will be evaluated during site characterization through monitoring of the ambient in situ water potential and numerical analyses (Section 8.3.1.2).

The numerical modeling results reported here are preliminary but are indicative of the kinds of analyses that can be performed through numerical simulations. Mathematical modeling is essential to gaining an understanding of the overall hydrologic system, and, as described in Section 8.3.1.2, considerable reliance is to be placed on these techniques. All the hydrologic data obtained during site characterization are ultimately to be synthesized in a comprehensive model for the flow of moisture within the unsaturated zone at Yucca Mountain.

Because of the presence of the natural geothermal gradient, moisture flow within the unsaturated zone at Yucca Mountain is not strictly isothermal. Thermal logging of drillhole USW G-1 yielded a mean gradient of 1.35°F/100 ft (24.6°C/km) (Tien et al., 1985) which suggests a temperature difference of about 13°C between the water table and land surface. A temperature difference of this magnitude probably has very little effect on the mechanics of liquid-water movement. Reda (1985b), for example, found experimentally that the intrinsic permeability of a sample of the Topopah Spring welded unit remained constant at 3.0×10^{-19} m^2 to within 10 percent over the temperature range from 25 to 90°C. The largest effect probably would be that of an increase in effective hydraulic conductivity with depth due to the reduction of the viscosity of water with increasing temperature. The change in water viscosity due to its temperature dependence over the thickness of Yucca Mountain could be expected to produce a maximum fractional change of hydraulic conductivity of about 30 percent. However, this effect probably is small compared to the variability in hydraulic conductivity arising from rock-matrix heterogeneity and inherent errors of measurement. The thermal expansivity of water would produce a change in water density of no more than about 0.5 percent and can thus be regarded to be a negligible effect.

A more likely but untested effect of the geothermal gradient within the unsaturated zone would be to induce an upward migration of moisture as water vapor, compensated by a downward return flow of liquid water. As described briefly in Section 3.9.3, the physics of the phenomenon is based on the presumption that liquid water and water vapor are in local thermodynamic phase equilibrium within the pore and fracture space and, thus, that the dependence of temperature on depth will produce a water-vapor concentration gradient aligned with the geothermal gradient. Consequently, a diffusive flux of water vapor would be induced upwards parallel to the geothermal gradient. Ross (1984) analyzes the efficacy of such a process within a porous medium having properties and under conditions similar to those expected for the Yucca Mountain site. He concludes that unless the net infiltration rate is less than 0.03 mm/yr the effects of upward water vapor diffusion are likely to be negligible compared to the matric-potential driven movement of liquid water. However, this transport mechanism may be considerably more pronounced in highly fractured unsaturated media in which the upward movement of water vapor could occur through the air-filled fracture openings, especially if driven additionally by bulk-gas flow (Montazer and Wilson, 1984; Montazer et al., 1985). At Yucca Mountain this effect could be of significance within the thick, fractured, repository TSw unit at the low rates of liquid water percolation (0.5 mm/yr) that may be occurring with this unit. Using temperature data obtained from test well USW UZ-1, Montazer et al. (1985) conclude that the ambient temperature gradient could produce an upward bulk-gas flux of 1.25 to 2.5 m/yr within the unsaturated zone. If the gas were saturated with respect to water vapor, such upward flow would produce an upward advective moisture flux of about 0.025 to 0.05 mm/yr under present conditions. Gas-pressure monitoring in test well USW UZ-1 shows a well-defined barometric response. It is unknown whether gas pressure variations at depths appropriate to the repository TSw unit would be sufficient to induce significant bulk gas flow. Nevertheless, the analysis of the hydrologic system within the unsaturated zone at Yucca Mountain, especially under nonisothermal, barometrically varying conditions, must consider the simultaneous, coupled flow of gas and moisture, the latter occurring both as liquid water and water vapor. Field measurements in surface-based boreholes, experiments in the exploratory shaft, and theoretically based modeling studies, as described in Section 8.3.1.2.2, are intended to address these issues.

3.9.4 GROUND-WATER VELOCITY AND TRAVEL TIME

Issue 1.6 of the issues hierarchy (discussed in the introduction to this document) addresses the performance objective defined in 10 CFR 60.113(a)(2): "The geologic repository shall be located so that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years...". The following discussion addresses this issue, focusing on that portion of the hydrogeologic system extending from the disturbed zone to the accessible environment. The components of this system which must be considered include: (1) the hydraulic properties of the formations through which the water will flow; (2) the present hydrologic conditions in the vicinity of the proposed repository; and (3) the locations and lengths of the flow paths between the disturbed zone and the accessible environment. The data and information required to assess the influences of these components on ground-water velocity and travel times are presently limited, and will be supplemented by the hydrologic investigations discussed in Section 8.3.1.2. The preliminary estimates of ground-water velocities and travel times presented here are based on sparse data and qualitative observations of hydrologic processes from limited field investigations.

Issue 1.6 addresses ground-water flow from the edge of the disturbed zone to the accessible environment. Based on the NRC Draft Generic Technical Position Paper on the Disturbed Zone (NRC, 1986b) the edge of the disturbed zone will be assumed conservatively to be 50 m below the repository level for this preliminary analysis. The actual extent of the disturbed zone will be determined during site characterization (Section 8.3.5.12.5). Based on the proposed amendments (NRC, 1986a) to 10 CFR Part 60, the accessible environment is located beyond 5 km from the outer boundary of the repository underground facility.

Section 3.9.3 presents the current conceptual model of the ground-water flow system at Yucca Mountain. This model (Figure 3-46) considers water moving downward beneath the repository in the unsaturated zone until it reaches the water table. Flow in the unsaturated zone is predominantly in the vertical direction, although lateral flow is a possibility. Once it reaches the water table, the flow in the saturated zone is generally horizontal to the accessible environment in a direction controlled by both the hydraulic gradient and the properties of the fractured medium. It is expected that flow to the accessible environment will be generally down gradient, with some directional variability induced by the anisotropy of the fractured rock matrix. The travel time estimates made below are based on this model, because it appears to be the most reasonable based on present understanding of the flow system and the present limited data base. As more data become available and our understanding of the system improves, the model will be modified, and the resulting travel time estimates adjusted accordingly.

3.9.4.1 Ground-water travel time in the unsaturated zone

Estimates of pre-waste emplacement ground-water travel times through the unsaturated zone have been made using the model described in Sinnock et al. (1986). This model makes the following assumptions:

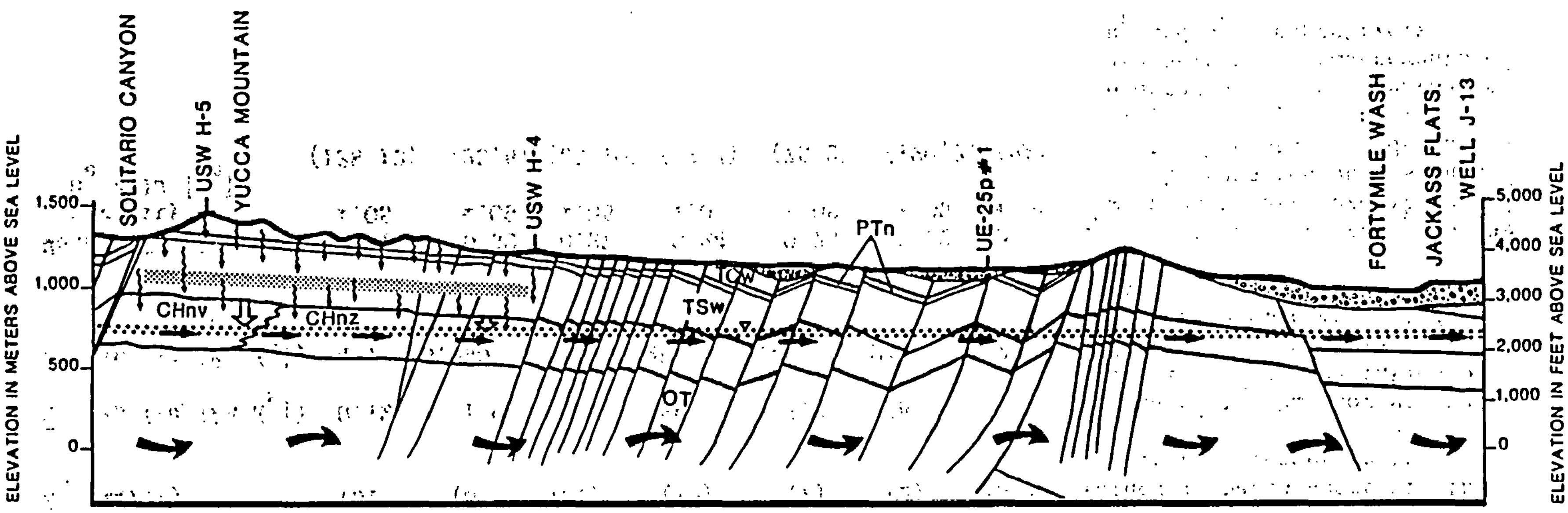
1. Moisture flow in the unsaturated zone occurs under steady state conditions in which the vertical flux of moisture within the deep unsaturated zone is equal to the ambient hydraulic conductivity.

2. The unsaturated-zone flux below the disturbed zone is vertically downward and uniformly distributed in time and space.

3. The ambient (effective) hydraulic conductivity through the matrix varies spatially as a function of saturation. Under conditions of a unit vertical hydraulic gradient (Weeks and Wilson, 1984), the vertical volumetric flux through the matrix becomes numerically equivalent to the unsaturated matrix hydraulic conductivity at the existing saturation level. As the saturation reaches 100 percent, the matrix is assumed to conduct water at a rate numerically equivalent to the saturated conductivity. Any remaining flux is assumed to travel through fractures, even though fracture flow may be initiated at lower saturation values.

4. Water does not move rapidly through fractures that are not connected to the surface until fluxes approach the saturated matrix hydraulic conductivity. This is due to the strong negative capillary pressures exerted by the pores of the matrix, which draw water away from the fractures (Sinnock et al., 1984; Wang and Narasimhan, 1984; Montazer and Wilson, 1984).

Parameters used in the travel-time calculations are shown in Table 3-30 (Sinnock et al., 1986). In addition, the initial flux was taken to be 0.5 mm/yr. This figure is based on Wilson (1985) using "two lines of evidence:



ALLUVIUM & TIMBER MOUNTAIN TUFF

DESIGN REPOSITORY (THICKNESS EXAGGERATED)

WATER TABLE

FLUX THROUGH THE UNSATURATED ZONE

UNSATURATED-ZONE FLOW PATHS USED FOR TRAVEL TIME CALCULATIONS

SATURATED-ZONE FLOW PATH FOR WATER THAT HAS PASSED THROUGH THE REPOSITORY LEVEL

DEEP SATURATED-ZONE FLOW PATHS FOR WATER THAT HAS NOT PASSED THROUGH THE REPOSITORY LEVEL

TCw	TIVA CANYON WELDED UNIT
PTn	PAINTBRUSH NONWELDED UNIT
TSw	TOPOPAH SPRING WELDED UNIT
CHnv	CALICO HILLS NONWELDED VITRIC UNIT
CHnz	CALICO HILL NONWELDED ZEOLITIC UNIT
OT	OLDER TUFF UNIT

0 0.5 1 MILES

0 0.5 1 KILOMETERS

Figure 3-46. Conceptual hydrogeologic section from Solitario Canyon northwest of the site, to well J-13 in Jackass Flats. Modified from Scott and Bonk (1984).

Table 3-30. Parameters used in travel-time calculations for the unsaturated zone[a] (page 1 of 2)

Parameter	Hydrogeologic unit[b]							Remarks
	TSw	CHnv	CHnz	PPw	PPn	BFw	BFn[c]	
Vertical hydraulic gradient, i	1.0	1.0	1.0	1.0	1.0	1.0	1.0	i = grad (ψ + z), where ψ is the pressure head and z the elevation head. If | grad ψ | << 1, $i_x \approx i_y \approx 0$ and $i_z \approx 1$. This implies vertical gravity flow.
Geometric mean saturated-matrix hydraulic conductivity $\bar{K}_s$ (mm/yr)[d]	0.72	107	0.54	88	22	118	22	K_s = exp (mean [ℓn (K_s)])
	(31)	(8)	(31)	(10)	(7)	(2)	(NA)[e]	Values in parentheses are the number of measurements.
$\bar{K}_s$ exp (-σ [ℓn K_s])	0.12	1.9	0.037	29	3.3	58	3.3	Values of K_s that correspond to a ± 1 standard deviation of ℓn(k_s) (± σ [ℓn K_s]) around the arithmetic mean of ℓn (K_s).
$\bar{K}_s$ exp (+σ [ℓn K_s])	4.1	6,090	7.6	261	142	240	142	
Mean effective porosity n_e ± 1σ [n_e]	0.11 ±.05	0.32 ±.09	0.27 ±.05	0.24 ±.06	0.25 ±.06	0.22 ±.09	0.25 ±.06	$\bar{n}_e = \bar{n}_b (1-\bar{S}_r)$, where n_b is the mean bulk, dry porosity and $\bar{S}_r$ is the mean residual saturation. The standard deviation $\sigma[n_e] = (1-\bar{S}_r)\ \sigma\ [n_b]$. Ordered pairs in parentheses are number of measurements of n_b and S_r, respectively.
	(138,12)	(23,6)	(65,10)	(27,4)	(75,2)	(120,2)	(NA)	
Range of thicknesses	0-72	0-135	0-133	0-44	0-122	0-91	0-55	Thicknesses between disturbed zone and water table for area

Table 3-30. Parameters used in travel-time calculations for the unsaturated zone[a] (page 2 of 2)

Parameter	Hydrogeologic unit[b] TSw	CHnv	CHnz	PPw	PPn	BFw	BFn[c]	Remarks
Range of thicknesses (continued)								within the design repository boundaries.
(m)[f]	(98.5)	(95.3)	(94.5)	(83.2)	(63.1)	(25.6)	(7.5)	Values in parentheses are percentages of total repository area underlain by the units.
Empirical constant ϵ	5.9	4.2	7.0	4.0	5.2	4.6	5.2	Empirical constant that represents the effects of the relationship between pore-size distribution and saturation on the amount of the effective porosity, n_e, available for flow; the effect of the empirical constant is to reduce flow area and thus increase particle velocity relative to values calculated using q/n_e.

[a]Source: Sinnock et al. (1986).
[b]TSw = Topopah Spring welded unit; CHnv = Calico Hills vitric unit; CHnz = Calico Hills zeolitic unit; PPw = Prow Pass welded unit; PPn = Prow Pass nonwelded unit; BFw = Bullfrog welded unit; BFn = Bullfrog nonwelded unit.
[c]Assumed to be hydrologically identical to PPn.
[d]Saturated conductivity and effective-porosity data are from Sandia National Laboratories Tuff Data Base (SNL, 1985).
[f]Range of thickness, Sandia National Laboratories Interactive Graphics Information System (IGIS) (SNL, 1985).
[e]NA = Not available.

(1) calculations of flux in the proposed host rock, based on field and laboratory evidence; and (2) an estimate of the recharge rate beneath the Yucca Mountain area, based on regional relationships developed among precipitation, altitude, and recharge rate."

Table 3-31 provides a summary of the travel times for the 0.5 mm/yr flux (Sinnock et al., 1986). As this table shows, the minimum (fastest) travel time through the unsaturated zone of more than 9,000 yr greatly exceeds the 1,000 yr required to satisfy the issue.

In an attempt to assess the sensitivity of the travel time to variations in flux, Sinnock et al. (1986) used an initial flux of 1 mm/yr, double the bounding value estimated by Wilson (1985). This analysis resulted in a minimum travel time of about 3,700 yr, still greater than the amount of time required to satisfy the issue.

The analysis presented here and discussed in detail in Sinnock et al. (1986) and DOE (1986) is considered preliminary. However, the modeling effort has attempted to use the best available data, and it is believed that the results obtained are realistic. Plans to develop this model further and to extend the data base are presented in Section 8.3.1.2.2.

3.9.4.2 Ground-water travel time in the saturated zone

For the saturated zone, the assumed flow path extends from the eastern edge of the primary repository area southeastward for 5 km to the accessible environment (Figures 3-28 and 3-25) through the tuffaceous beds of Calico Hills and the welded Topopah Spring Member or the welded Crater Flat Tuff (Prow Pass or Bullfrog Member). Estimates for ground-water travel times along this travel path have been made using the following assumptions (DOE, 1986):

1. Darcian flow applies.

2. Flow paths are parallel to the hydraulic gradient and are nearly horizontal.

3. The water-level measurements shown in Figure 3-28 (Robison, 1986) provide a reasonable estimate for the hydraulic gradient along the flow path.

4. The system is isotropic within each unit, and hydraulic conductivity values obtained from hydraulic tests of wells in the southeastern part of the Yucca Mountain area are representative of the values along the flow path.

5. Calculated effective porosities from Sinnock et al. (1984) are of a magnitude that will tend to result in minimum travel times calculated for flow in the saturated tuffaceous beds of Calico Hills.

The hydraulic gradient has been estimated using water-level altitudes of 730.4 m at drillhole UE-25b#1 and 728.3 m at well J-13 (Figure 3-28). An

Table 3-31. Summary of unsaturated zone travel time for vertical flux of 0.5 mm/yr[a]

Travel path[b]	Travel time (yr)
Minimum	9,345
Mean	43,265
Maximum	80,095

[a]Source: Sinnock et al. (1986).
[b]Travel paths are from the repository horizon to the water table and are based on multiple modeling scenarios as discussed in Sinnock et al. (1986).

examination of the data for well UE-25P#1 (Craig and Robison, 1984) suggests that the water table is located approximately at the interface between the Calico Hills and the Topopah Spring units at this point (approximately 3,000 m from both the edge of the repository and well J-13). Using the principle of conservation of mass, hydraulic gradients have been estimated for each of the units as shown in Table 3-32. Uncertainties in these estimates include the following components: (1) with very low gradients, small errors in the measurements of water levels can have significant effects on the value of the gradient; (2) the measured water level at well J-13 could be expected to be lower than the static water level because of pumping, thereby resulting in a steeper estimated gradient; and (3) vertical components of flow may be present. Because vertical flow would have the effect of lengthening the flow path, the assumption of horizontal flow probably is conservative, although Waddell et al. (1984) indicate the controls on vertical and horizontal flow at Yucca Mountain are variable and generally unknown.

Table 3-32 shows these values and provides estimates for travel times through the Calico Hills and the Topopah Spring units. On the basis of these estimates, the cumulative travel time through the saturated zone is about 172 yr. This value is different from that presented in DOE (1986), due to the use of well UE-25b#1 instead of USW H-4; the former was chosen in this analysis as being more representative of regional trends in the hydraulic gradient (Figure 3-28).

This estimate of travel time is considered to be conservative, based on the assumptions mentioned above and on the fracture effective porosities reported by Sinnock et al. (1984). These effective porosities were calculated by multiplying the fracture density from Scott et al. (1983) by the effective aperture calculated from a relationship provided by Freeze and Cherry (1979). The resulting effective porosities are considered to be reasonable estimates for fracture flow in the saturated zone. However, empirical estimates of saturated effective porosity for both matrix and fracture flow range from 8 to 12 percent for the Topopah Spring welded unit (Sinnock et al., 1984); 2.7 to 8.7 percent for Topopah Spring Member

Table 3-32. Estimates for ground-water travel times through the saturated zone

Parameter	Unit: Tuffaceous beds of Calico Hills	Unit: Topopah Spring Member
Length of path (m)	3,000	2,000
Hydraulic conductivity (m/yr)[a]	69	365
Hydraulic gradient[b]	5.9×10^{-4}	1.1×10^{-4}
Darcy velocity (m/yr)[c]	4.1×10^{-2}	4.0×10^{-2}
Calculated bulk effective fracture porosity[d]	4×10^{-4}	2.8×10^{-3}
Particle velocity (m/yr)[e]	103	14
Travel time (yr)[f]	29	143

[a]Hydraulic conductivity for Calico Hills from Lahoud et al. (1984) and Thordarson (1983); Topopah Spring from Thordarson (1983).
[b]Based on water levels at drillhole UE-25 b#1 and at well J-13 (see Figure 3-28). The estimates for the hydraulic gradient for each of the units has been based on conservation of mass between drillhole UE-25b#1 and well J-13.
[c]Darcy velocity = (hydraulic conductivity) x (hydraulic gradient).
[d]Data from Sinnock et al. (1984).
[e]Particle velocity = (Darcy velocity)/(bulk effective porosity).
[f]Travel time = (length of path)/(particle velocity).

(Thordarson, 1983); and 20 to 30 percent for the Calico Hills vitric unit (Sinnock et al., 1984). Use of more realistic (less conservative) values of effective porosity would be likely to lead to a saturated ground-water travel time at least ten times greater (i.e., approximately 1,700 yr) than that indicated in Table 3-32.

3.9.4.3 Retardation and thermal effects

The ground-water travel times estimated for the saturated and unsaturated zones at Yucca Mountain are presently based on Darcy's law and Richard's equation. In fact, ground-water flow through fractured unsaturated media tends to be dominated by the matrix hydraulic conductivity. Water moving through a fractured system may travel into and out of the matrix from the fractures as it moves down gradient (DOE, 1986). This is due to the differences in matric, osmotic, thermal, and pressure potentials across the fracture-matrix interface. This leads to a lengthening of the ground-water travel path for individual ground-water molecules, thereby increasing ground-water travel times.

Other factors may affect ground-water travel time, including dispersion, the existence of faults or impermeable zones along the travel path, the vertical movement of water in the saturated zone, and the upward movement of moisture in the unsaturated zone. At this time it is uncertain whether some or all of these mechanisms exist along the travel path. Efforts will be made during site characterization to determine the existence of these and other features, and also to estimate the effect of these on pre-waste-emplacement ground-water travel times.

The possible effects of thermal gradients on the ground-water flow system at Yucca Mountain are unknown at this time. Thermal gradients may be causing upward flow in the unsaturated zone (Wilson, 1985), although this is only conjective at present. As mentioned in Section 3.7.3, little information exists on thermal gradients in the saturated zone. The information available is from isolated locations that give little indication of the thermal gradient in the vicinity of Yucca Mountain. Such information will be collected during site characterization, and its effect on the ground-water flow system will be evaluated at that time (Section 8.3.1.2.2).

3.9.5 HYDROCHEMICAL CONFIRMATION OF GROUND-WATER BEHAVIOR

This section presents information concerning hydrochemical evaluation of the ground-water system, and the question of whether the site will meet the performance objective for pre-waste emplacement ground-water travel time as required by 10 CFR 60.113(a)(2) (Issue 1.6). Section 3.9.1.3 provides data and descriptions of the hydrochemical evaluation of the ground-water system, including possible origin, travel paths and flow rates. Section 3.7.3 provides further hydrochemical data for the hydrogeologic study area. This section deals primarily with problems associated with interpreting ground-water velocities derived from radiocarbon data.

3.9.5.1 Unsaturated zone

Complete hydrochemical or isotopic analyses are not available for pore water taken from the site's unsaturated zone. Methods to extract this water in an uncontaminated state are still under development. Yang (1986) presents preliminary calcium and sodium concentration data; his studies indicate that calcium concentrations are elevated in the unsaturated zone and dominate over sodium. Section 8.3.1.2.2 presents plans for characterizing the chemical and isotopic composition of the pore water. This information will be used to understand potential interactions of pore water with the waste canister and to define flow paths and velocities in the unsaturated zone.

3.9.5.2 Saturated zone

Summaries of the hydrochemical characteristics of the water in the saturated zone in the Yucca Mountain area, of the hydrochemical mechanisms controlling these characteristics, and of the hydrochemical evidence for ground-water origin, aquifer mixing and ground-water residence time are presented in Sections 3.7.3 for the hydrogeologic study area and in Section 3.9.1.3 for the site. As discussed in Section 3.9.1.3, only limited data exist in the immediate vicinity of Yucca Mountain, and those data tend to be mainly radiocarbon data. This section elaborates on the difficulties in interpreting ground-water velocities from radiocarbon data which have not been adequately modeled for initial carbon-14 activity. Plans for obtaining additional hydrochemical data are presented in Sections 8.3.1.2.2 for the unsaturated zone and 8.3.1.2.3 for the saturated zone.

The reported radiocarbon dates of ground water at Yucca Mountain have been uncorrected, apparent ages (Section 3.7.3.2.1) (Benson and McKinley, 1985; Claassen, 1985). Given a series of assumptions examined in more detail below, such ages may represent the time since ground water was isolated from the CO_2 gas reservoir of the atmosphere or the unsaturated zone (i.e., the time since the water entered the water table beneath Yucca Mountain). Uncorrected ages are realistic when no carbon-12 dilution has occurred to the initial carbon-14 by the dissolution of carbon-14-free carbonate minerals. Claassen (1985) indicates that this is the case in the tuffaceous aquifer, since these formations are virtually carbonate-free. If such dilution occurs, the apparent radiocarbon ages may be an upper limit of the ground-water age (Section 3.7.3.2.2).

The other major assumption underlying the apparent ages relates to the initial carbon-14 composition of the infiltrating water. Uncorrected ages assume that this water was in isotopic equilibrium with a gaseous reservoir at 100 percent modern carbon (pmc). This is generally valid, since both the atmosphere (before nuclear weapons testing) and soil gas (gas in the unsaturated zone in a well mixed or low CO_2 gas-residence-time system) have this composition. In a poorly mixed system with long CO_2 gas residence times where the carbon-14 in the CO_2 gas has decayed, the radiocarbon reservoir is at less than 100 pmc. In such a case, the apparent age of the ground water is greater than the time it has been in the aquifer (by an amount proportional to the difference between 100 pmc and the carbon-14 concentration in the equilibrating CO_2 gas).

Yang et al. (1985) have shown that the carbon-14 concentration of the CO_2 gas in the soil zone can be as low as 34.2 (±1.5) pmc in the unsaturated zone at 368 m below the surface. The apparent age of a ground-water sample equilibrated with such gas is really equal to the age of the gas in the unsaturated zone (without isotopic mixing) plus the residence time of the ground water in the aquifer since equilibration (without isotopic dilution). The apparent age is thus older than the true ground water residence time. Since isotopic re-equilibration with CO_2 gas can occur throughout the unsaturated zone, apparent ages of the unsaturated zone water (time since precipitation) are not reliable.

Well documented and tested models of initial ground-water carbon-14 activity exist. Some of these models (Mook, 1976, 1980; Fountes and Garnier,

1979) are particularly well suited for modeling waters which equilibrate with CO_2 gas in the unsaturated zone and then enter the water table. Such models can be used to examine the apparent difficulties in interpreting carbon-14 data from Yucca Mountain (Section 8.3.1.2 for plans for their use). Such models, which are said to give corrected ages, do not actually perform corrections of an error, but rather, they simply do not ignore the hydrochemical processes which control carbon-14 behavior.

Kerrisk (1987) has pointed out that at Yucca Mountain, gaseous CO_2 from the unsaturated zone may be added to or exchange with the carbonate of the saturated zone water. This process could lead to apparent ages that are younger than the true ages of the water in the saturated zone.

An accurate knowledge of initial carbon-14 activity is less important in calculating relative ground-water ages or velocities than it is in determining absolute chronologies. Ground-water velocities can be estimated by dividing the distance between two points along a hydrologic flow line by the carbon-14 age difference of the water at the two points. Consistent errors in estimating initial activity tend to cancel, resulting in relative ages which are more accurate than are the individual absolute ages. This is not the case when calculating the velocity of water to a point where the carbon-14 age is known from the assumed point of present day recharge (absolute age zero). Mixing (i.e., the two points are not actually on the same hydrodynamic flow line or the line has moved during the transit of the parcel of water) is also not considered in this calculation. These two difficulties apply to the results of Claassen (1985) who states, "For example, assume recharge near the head of Fortymile Canyon occurred 17,000 years ago and flowed to the lower end of the Canyon, where it is sampled. The velocity that is calculated, 7 m/yr, must be a maximum. Because recharge may occur anywhere but not necessarily everywhere along surface drainageways, no probable minimum velocity can be calculated. The absence of water older than about (apparent age) 10,000 yr. B.P. even near the head of Fortymile Canyon, would favor velocities slower than 4 m/yr." The planned use of initial carbon-14 modeling and relative dating along flow paths to resolve apparent difficulties of interpretation is described in Chapter 8.3.1.2.3.

3.9.6 MONITORING AND VERIFICATION

This section discusses the monitoring and verification program designed to assess hydrologic conditions at and near Yucca mountain. The program will also provide an historical background to permit detection of changes in baseline conditions during repository construction, operation, and following closure.

Data from the existing monitoring program are included in Section 3.9.1. The current program consists of 25 boreholes which penetrate the saturated zone and a single instrumented hole in the unsaturated zone. Details of the construction, instrumentation, and monitoring of these holes is discussed in Section 3.9.1.

The primary functions of the program are to provide a data base against which future observations maybe compared, to provide information for verification of ground-water models, to evaluate parameters for use in travel-time calculations, and to collect data for the construction of a potentiometric-surface map and determination of ground-water flow directions. The current program provides this information and will be continued. However, additional data are required to provide the level of detail necessary for a thorough understanding of the hydrologic system at Yucca Mountain. Additional data on ground-water geochemistry, water potential temperature variations, etc., will be collected to fulfill the data requirements of the various conceptual models proposed for the site (Sections 8.3.1.2.2 and 8.3.1.2.3).

In order to provide an expanded data base, additional test holes will be added to the monitoring network during site characterization. The new holes will be used for various types of data aquisition, including determination of the hydraulic nature of structural features, measurement of the hydraulic gradient, estimation of ground-water flowpaths, and calculation of various hydraulic parameters in both the saturated and unsaturated zones. Detailed plans for these holes are included in Section 8.3.1.2 along with specific plans for monitoring and use of the resultant data.

3.9.7 LOCAL GROUND-WATER USERS

This section identifies all production wells that are located near the Yucca Mountain site. It is possible that withdrawals from these wells could affect the local flow system. Available pumping information that will aid in identifying these effects is presented. These data, in conjunction with results from planned modeling and field studies will be used to quantify and qualify any potential changes to the local flow system. Plans for further studies are presented in Section 8.3.1.2.

There are two wells located proximally to the Yucca Mountain site that withdraw water on a regular basis. Wells J-12 and J-13, located approximately 12 km and 8 km southeast of the Yucca Mountain site, respectively, are utilized and controlled by the DOE to support activities in the southwestern part of the Nevada Test Site (refer to Section 3.8.1 for a discussion of regional ground-water users).

Water from wells J-12 and J-13 is produced from the Topopah Spring Member of the Paintbrush Tuff, which constitutes the lower portion of the welded tuff aquifer (Section 3.6.1). The Topopah Spring Member occurs at a depth of approximately 180 to 347.2 m at well J-12, and 207.3 to 449.6 m at well J-13 (Thordarson et al., 1967; Claassen, 1973). Pumping-test and water-level data for both wells are shown in Table 3-33. Well-construction information can be found in Thordarson et al. (1967), Thordarson (1983), Young (1972), and Claassen (1973). Table 3-34 summarizes water production for wells J-12 and J-13 from 1983 through 1985. Water-quality data are presented in Section 4.1.2.2 of Chapter 4.

Wells J-12 and J-13 have been pumped intermittently since their completion. Before 1968, well J-12 was pumped at rates in excess of 2,000 m^3/d. After the wellbore was cleaned and deepened in 1968, production capabilities

Table 3-33. Pumping test and water-level data for wells J-12 and J-13 from 1960 through 1969[a]

Date of pumping test	Water level (m) Datum: MSL[b]	Specific capacity ($(m^3/d)/m$)	Pumping rate (m^3/d)	Draw-down (m)	Duration of test (h)
		WELL J-12			
01/27/60	727.6	--[c]	--	--	--
11/01/60	--	1,700	2,080	1.2	2
08/22/62	726.7	1,000	2,110	2.10	1
07/27/65	--	2,800	2,020	0.73	83
07/25/68	727.0	220	4,250	19.54	1
08/24/68[d]	727.3	850	4,880	5.78	5
04/21/69	727.3	1,600	4,850	3.02	4
		WELL J-13			
02/18/64	728.5	420	3,800	9.11	3
02/18/64	727.9	310	2,800	12.31	96
03/31/64	729.4	--	--	--	--
04/21/69	728.2	540	3,640	6.77	4

[a]Modified from Claassen (1973).
[b]MSL = mean sea level.
[c]-- indicates no data.
[d]Well bore cleaned and deepened to 347.2 m. Test data indicated downhole sloughing, resulting in decreased hydraulic conductivity. Original total depth: 270.4 m.

Table 3-34. Water production from wells J-12 and J-13 from 1983 through 1985[a,b]

Well	1983 Gallons	1983 Acre-feet[c]	1984 Gallons	1984 Acre-feet	1985 Gallons	1985 Acre-feet
J-12	25,498,500	78.2	26,058,400	80.0	25,049,800	76.9
J-13	42,148,700	129.3	40,349,300	123.8	37,811,000	116.0
Total	67,647,200	207.5	66,407,700	203.8	62,860,800	192.9

[a]Production figures are for water year, October 1 through September 30.
[b]Source: Witherill (1986).
[c]To convert from acre-feet to cubic meters, multiply by 1233.489.

exceeded 4,500 m^3/d. Well J-13 has been shown to be capable of producing in excess of 3,500 m^3/d of water (Claassen, 1973). The specific capacity of the well underwent a slight decline in 1964 shortly after completion. Claassen (1973) hypothesized that the well was not fully developed during the 1964 tests. Subsequent pumping tests performed in 1969 support this hypothesis, and the specific capacity of 540 m^3/d/m is considered the most reliable measurement.

Pumping tests performed after 1968 on well J-13 produced drawdowns of less than seven meters with pumping rates in excess of 3,500 m^3/d (Table 3-33). Figure 3-47 indicates that even with well J-13 in continuous service, declines in the water level have been minimal. This suggests that the short-term effects of pumping on the regional potentiometric surface are probably negligible. The effects of long-term pumping on the local potentiometric surface are unknown and remain to be investigated (Robison, 1984). Tests planned during site characterization for evaluating the potential effects of repository development on the local potentiometric surface are presented in Sections 8.3.1.2.3.1 and 8.3.1.16.2.1.

The water which will be needed for site characterization activities probably will be drawn from wells J-12 and J-13. It is possible that a substitute source may be located and developed (Morales, 1986). Preliminary estimates of the amount of water necessary for site characterization activities, and the construction and operation of a geologic repository at Yucca Mountain, are presented in Section 3.8.1.

Other drillholes exist near the site but are pumped only periodically to obtain hydrologic and hydrochemical information. These test holes have not been used to supply water. Section 1.6 provides a discussion of all existing exploratory drillholes in the Yucca Mountain area.

3.9.8 PALEOHYDROLOGY

Discussion of the paleohydrology of the south-central Great Basin, including Yucca Mountain, is presented in Section 3.7.4. In this section, the discussion is limited to those past and probable future hydrologic conditions that may directly affect a repository at Yucca Mountain.

Winograd and Szabo (1986) concluded that there was a progressive lowering of water table in the south-central Great Basin during the Quaternary, and that "a continued decline of the regional water table in the next 10^5 to 10^6 yr (and beyond?) in response to increasing aridity and to lowering of ground-water base level" is likely (Section 3.7.4). They noted, however, that this progressive water-table decline "does not preclude superimposed and relatively rapid cyclical fluctuations in water level in response to glacial (i.e., pluvial) and interglacial climates of the Pleistocene." Preliminary field evidence and the results of a computer-model analysis bearing on past and possible future water levels beneath Yucca Mountain are outlined below.

Bish and Vaniman (1985) noted that nonwelded glass occurs both above and below the welded zone in the Topopah Spring Member (Tptw) of the Paintbrush Tuff. Bish and Vaniman (1985) state "the lower nonwelded vitric zone thins

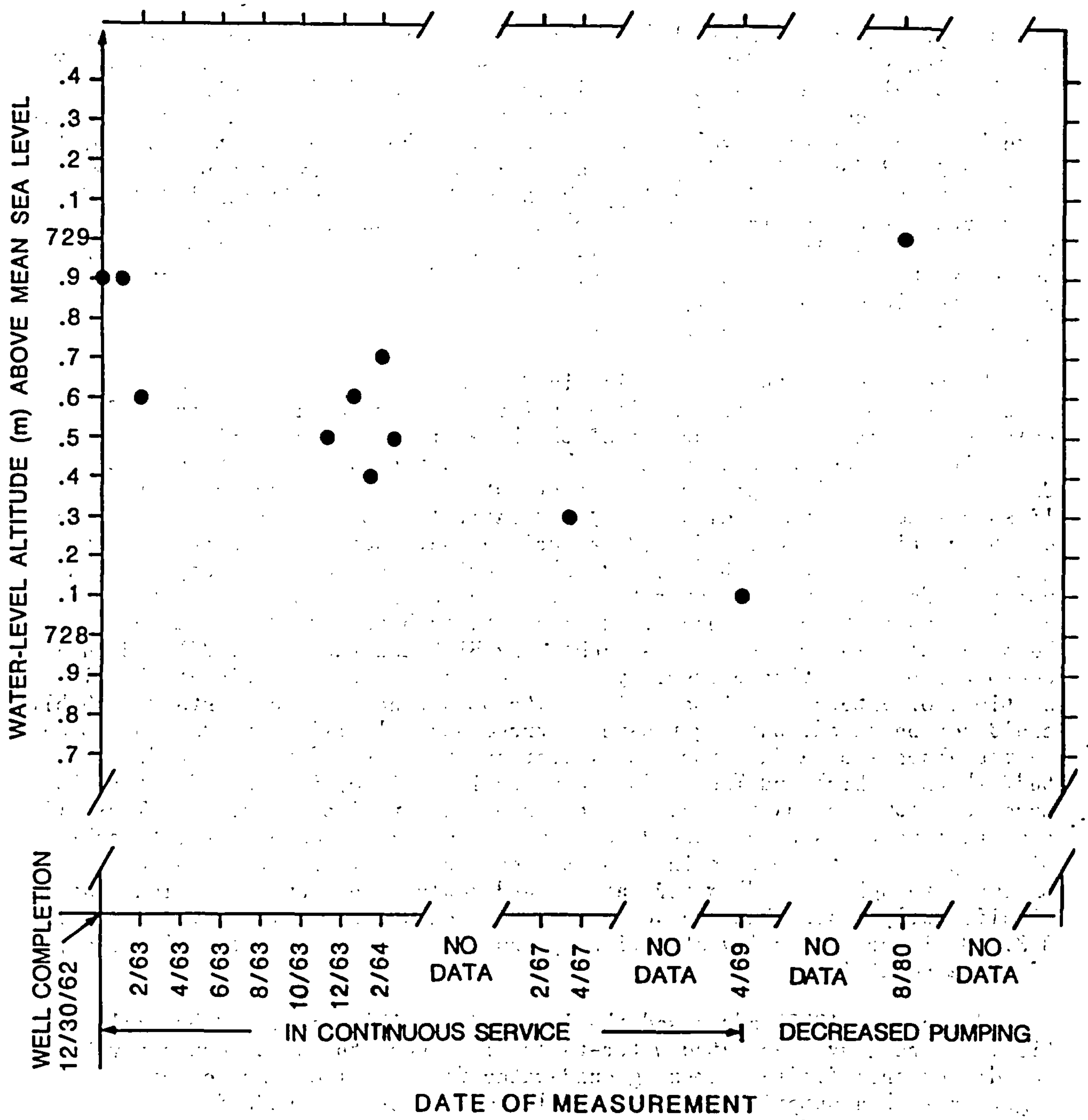


Figure 3-47. Water levels in well J-13 since completion. Modified from Thordarson (1983).

and disappears to the east where stratigraphic dip and structural displacements bring the basal Tptw glassy zone closer to the static-water level. The vitric nonwelded material may have important paleohydrologic significance because the preservation of open shards and pumice made of nonwelded glass is rare below past water levels (Hoover, 1968)." Where present, the base of the lower nonwelded vitric tuff occurs about 80 to 100 m above the present water table. On the basis of mineralogy, Bish and Vaniman (1985) concluded, "The only apparent change in phase assemblage near the water table in Yucca Mountain is the alteration of vitric tuff of Calico Hills and lower Topopah Spring Member." The observations by Bish and Vaniman (1985) suggest that past water levels beneath Yucca Mountain may never have been more than 100 m higher than the modern water levels.

To help assess the implication in Bish and Vaniman (1985) that the lowest position of vitric nonwelded tuff might be related to a stand of a paleo-water table, a contour map of the base of the lower vitric nonwelded tuff (in both the Topopah Spring Member and in the tuffaceous beds of the Calico Hills) will be prepared and contrasted with the modern water table. If such a contour map indicates (1) a relatively smooth surface at the base of the vitric nonwelded tuff, (2) a surface that locally cross-cuts stratigraphic horizons in the tuffs, and (3) a surface that climbs sharply to the north as does the modern water table beneath Yucca Mountain, then it is possible that the porous nonwelded vitric tuffs have indeed been altered below a paleo-water table, as suggested by Bish and Vaniman (1985). Such a contour map would then presumably mark the stand of water table at the time or times of alteration of the tuffs. The occurrence of such a stand probably could not be dated, but might have occurred several million years ago. Even in the absence of a date for the alteration, the base of the nonwelded vitric tuff shown on Bish and Vaniman's cross sections (1985) is tens of meters to more than 100 m below the base of the proposed repository horizon. Thus, if the previously discussed work demonstrates the likelihood of a relationship of the paleowater table to the lowest occurrence of vitric tuff, a possible maximum (though undated) water-table stand would have been identified that is significantly lower than the repository horizon under consideration. Section 8.3.1.3 discusses the investigations planned to characterize the mineralogy of Yucca Mountain.

Czarnecki (1985) addressed the issue of possible past, and by implication, future pluvial-related water-table rises beneath Yucca Mountain with a two-dimensional finite element ground-water flow model of the region, together with assumptions about pluvial recharge on, and underflow into and from the region. He calculated a maximum increase in water-table altitude of about 130 m beneath the site of the proposed repository. Inundation of any part of the planned repository would require a water-table rise of more than 200 m. His analysis also suggests a past shortening by two-thirds of ground-water flow paths from Yucca Mountain to discharge areas in the southern Amargosa Desert. These discharge areas are still beyond the boundary of the accessible environment.

The analysis by Czarnecki (1985) may be considered conservative for several reasons. A 100-percent increase in precipitation during pluvial periods was assumed, resulting in a 15-fold increase in recharge from the modern rate (0.5 mm/yr) to about 8 mm/yr at Yucca Mountain. Czarnecki (1985) acknowledges that this recharge value, which was derived from the empirical

Maxey-Eakin water-budget method, probably is high. Half of the calculated recharge flux in the model was applied directly east of the proposed repository site, along a segment of Fortymile Wash. This flux causes about three-quarters of the computed water-table rise of 130 m. Czarnecki (1985) notes, however, that under a 100-percent increase in precipitation, large quantities of runoff might flow away from the area down Fortymile Wash and other drainageways. This would have the effect of decreasing the effective ground-water recharge to much less than the calculated values (Czarnecki, 1985).

Other considerations were noted by Czarnecki (1985) that might have resulted in a greater simulated water-table rise. Recharge into Fortymile Wash was limited to the main stream channel near Yucca Mountain. If recharge had been included along the full length of Fortymile Wash and its distributaries, which extend beyond the town of Amargosa Valley, then a greater water-table rise would have been simulated. Simulated development of discharge areas southeast of the town of Amargosa Valley helped to limit the water-table rise beneath the primary repository area. If this discharge were decreased because of the possible existence of marsh deposits or eolian silts or because of a greatly decreased ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity, then the simulated water-table rise might be greater. The model used by Czarnecki (1985) derived its parameters from a model presented in Czarnecki and Waddell (1984), which assumed that the ground-water system was in steady-state conditions. If the ground-water system was still equilibrating to recharge that may have occurred 10,000 to 20,000 years before present, then the values of transmissivity used in the model in Czarnecki (1985) might be too high. Large transmissivities used in recharge simulations would produce less water-table rise than if smaller transmissivities were used.

Extensive investigations are planned to better quantify the parameters of the hydrologic system in the Yucca Mountain region. These parameters will be used to model the hydrologic system more effectively and any variations induced by climatic or tectonic changes. Plans for these studies are discussed in Sections 8.3.1.2.1.4 and 8.3.1.2.2.9.

During pluvial periods of the Pleistocene, perched springs and seeps could have occurred along the flanks of Yucca Mountain and these might have resulted from recharge along the exposed up-dip portion of tuff units, with water moving down-dip to discharge sites along the flank of the mountain. No conclusive evidence for former springs has been observed, but additional investigations are planned, as outlined in Section 8.3.1.5.2.

Deposits along fault zones may provide additional evidence for changed hydrologic conditions. Along portions of the Bow Ridge fault, 1 km east of the eastern boundary of the proposed repository, Trench 14 has exposed deposits of carbonate, opal, and minor amounts of sepiolite (Vaniman et al., 1985; Taylor and Huckins, 1986; Voegele, 1986a,b). These deposits are discussed more extensively in Section 1.2.2.2.10. The origin of these deposits is under study, and the following hypotheses are being considered:

1. The deposits are the result of ground-water discharge along the fault, from the deep regional flow system and reflect former higher water levels, tectonic uplift of the deposits, or a combination of both.

2. The deposits are the result of discharge along the fault zone from a shallow ground-water flow system along the flank of Yucca Mountain.

3. The deposits are shallow soil features that resulted from rain water that moved downslope from the top of a nearby low hill, along the contact between the soil zone and bedrock, and accumulated at the fault zone. The water would have evaporated slowly, leaving precipitates of the minerals that were dissolved in the water. Present evidence from studies discussed in Section 1.2.2.2.10 supports this hypothesis (Vaniman et al., 1985; Taylor and Huckins, 1986; Voegele, 1986a).

Further investigations designed to determine the nature and origin of these deposits are discussed in Section 8.3.1.5.2.

3.10 SUMMARY

Chapter 3 discusses the data that are available and additional data that are needed for understanding the hydrologic aspects of the site. These data will be used to assist in resolving many of the postclosure and preclosure issues within the NNWSI Issues Hierarchy. This section summarizes the data that have been presented, and the plans identified in Section 8.3.1.2 for collecting the additional data needed to satisfy the performance and design issues.

3.10.1 SUMMARY OF SIGNIFICANT RESULTS

One of the primary issues to be satisfied during site characterization is: Do the data collected in order to describe the geohydrologic characteristics at the Yucca Mountain site provide the information required by the design and performance issues? Investigations of the geohydrologic system described in Section 8.3.1.2 include (1) understanding the regional hydrogeologic system; (2) describing the unsaturated- zone hydrologic system at the Yucca Mountain site; (3) describing the saturated zone hydrologic system at the site; and (4) presenting information required to support post-closure repository performance which requires that the geohydrologic setting be compatible with waste containment and isolation under both anticipated and unanticipated conditions and that ground-water travel time along the fastest pathway of likely and significant radionuclide travel be not less than 1,000 years.

The region surrounding Yucca Mountain is one of the most arid parts of the United States. The climate is typified by low rainfall, low humidity, high evaporation, high summer temperatures, and high wind velocities during the spring. Precipitation generally increases with elevation; average annual amounts range from 43 mm in Death Valley to 760 mm on the highest peaks of the Spring Mountains (Section 3.1).

Collection of precipitation data is planned throughout the region in order to characterize better the present-day precipitation as a function of topographic setting; rainfall intensity and duration characteristics are needed for rainfall-runoff models and for infiltration studies. Modern meteorological conditions also form a basis for interpreting historical records and predicting future conditions. The plans for collecting these data are presented in Section 8.3.1.2.1, 8.3.1.2.2, and 8.3.1.12.1.

Because of generally arid climatic conditions, there are no perennial streams in the regional hydrologic area. The limited surface water that does exist is restricted to short spring-fed reaches of the Amargosa River, small pools at some large springs, and some large springs and marshes in Alkali Flat and Death Valley. However, arroyos occasionally flood during convective rainstorms. Long-term flood records as a basis for predictions are few, but occasional flash floods and debris flows are anticipated. Erosion and deposition from flash floods and associated debris flows are among the most active geomorphic processes in the region, and they have a major role in the development of alluvial fans, denudation of mountainous landscapes, and the evolution of drainage-channel morphology.

Gages and other instrumentation are planned to be installed and operated in order to correlate streamflow events with precipitation. Streamflow and its characteristics will be studied in order to determine inundation, sediment transport, and erosion in the vicinity of the proposed repository surface facilities (Section 8.3.1.2.1).

Two hydraulic-engineering studies of flood-prone areas near Yucca Mountain provide a basis for estimating magnitudes and recurrence intervals of future floods (Section 3.2). Further studies will determine the magnitudes of probable maximum floods near the surface sites of proposed repository facilities (Section 8.3.1.16.1).

The nature and quantities of present and future infiltration or recharge need to be known better, especially at the site, including Fortymile Wash. Studies that include soil-moisture evaluations and chemical and isotopic analyses of waters from both the unsaturated and saturated zones are identified in Section 8.3.1.2 to provide this information.

Hydrogeologic conditions at the Yucca Mountain site are affected by the regional ground-water flow systems. The regional ground-water flow system originates as recharge at topographic highs within the hydrogeologic study area, and generally discharges at topographic lows. Other discharge areas are located where structural barriers to flow cause ground water to discharge. These discharge points are near Beatty, in the southeastern part of the Amargosa Desert, and in adjoining parts of Death Valley. Flow to these points is generally southward near Yucca Mountain and southwestward in areas east of Yucca Mountain. The hydrogeologic study area, having an area of about 16,200 km^2, has 10 identified and described hydrogeologic units. These range from an uppermost, discontinuous valley fill aquifer, through volcanic-rock aquifers and aquitards to a sequence of carbonate-rock aquifers and clastic-rock aquitards.

The ultimate source of nearly all ground water in the study area is precipitation on the basin. Because high-altitude areas generally receive more average annual precipitation, they generate more ground-water recharge than the valley floors, although recharge may also occur by infiltration of surface runoff in wash bottoms. Most of the higher mountains (recharge areas) are in the northern and eastern part of the study area. Flow from the higher areas to the north passes southward beneath Yucca Mountain to be discharged by springs and evapotranspiration.

The hydraulic conductivity of rock in the hydrogeologic study area is controlled by fractures, joints, faults, vapor-phase cavities, interstitial spaces, and bedding planes. The aquitards have low fracture hydraulic conductivity and negligible interstitial hydraulic conductivity. Where fractures and faults are present, open, and unsealed with rock material, hydraulic interconnection among the hydrogeologic units is effective in transmitting water if hydraulic gradients of sufficient magnitude are present. Ground water in transit within the system and beneath Yucca Mountain has been estimated to be 10,000 to 20,000 yr old.

A conceptual model for ground-water flow in the saturated zone in the vicinity of Yucca Mountain has been developed and is based on the following assumptions: (1) The rock containing the primary matrix porosity is homogeneous and isotropic, (2) Secondary porosity is controlled mostly by fractures; the volume of water stored in them is relatively small in comparison to that stored in the matrix, (3) Hydraulic conductivity of fractures is several orders of magnitude larger than the conductivity of the matrix, (4) Distances between fractures are small in comparison with the dimensions of the ground-water basin, (5) On a large scale, the orientation of fractures may be assumed random so that the system appears isotropic, i.e., a slightly different form of a porous medium with equivalent porous-media properties.

Estimated average annual ground-water recharge from precipitation for the hydrogeologic study area is 5.6 x 10^7 m^3 (Rush, 1970). The largest natural discharge point in the study area is the southeastern Amargosa Desert, where estimated average annual ground-water discharge is 3.0 x 10^7 m^3 (Walker and Ekin, 1963; Rush, 1970). The remaining discharge is distributed among several smaller discharge areas. At Yucca Mountain the specific fluxes based on a two-dimensional flow model range from 3.6 m^2/yr to 1.1 x 10^6 m^2/yr.

Major-ion chemistry of ground water in the region has been summarized but enough water-chemistry data are not yet available to develop a hydrochemical model to support conceptual-flow models, or to verify suggested ground-water flow paths (Section 3.7.3).

There is evidence for former, higher levels of the water table in the study area during the Plio-Pleistocene probably because increasing aridity associated with uplift of the Sierra Nevada resulted in lower precipitation with the Great Basin, which in turn has lead to a lowering of the water table. Also, flow-path lengths of ground water may have been shorter during the Plio-Pleistocene. However, current data based on climatic trends or evidence for past hydrologic conditions are insufficient to make reliable projections of future hydrologic conditions (Section 3.7.4). Section 8.3.1.5.2 discusses plans to evaluate further the potential effect of future climatic conditions on the hydrologic system at Yucca Mountain.

At the Yucca Mountain site, the water table is about 250 m below the proposed repository horizon. The proposed repository horizon is in turn, is about 300 m below land surface. It is not known at this time under what circumstances the water table might be expected to rise sufficiently to saturate an underground facility at the repository horizon. As discussed in Sections 3.7.4 and 3.9.8, there is no evidence that water levels were more than 100 m higher during the Quaternary Period, but evidence indicates that water levels may have declined during that time. The results of preliminary regional ground-water flow modeling studies indicate that the climatic regime is unlikely to produce water table rises over the next 10,000 years that could inundate the repository. This unlikely scenario is to be examined further, as described in Section 8.3.1.5.2.

The preliminary information presented in Section 3.8.1 and 3.8.2 suggests that siting a mined geologic disposal system at Yucca Mountain will not adversely affect local ground-water users or the ground-water system. As discussed in Section 3.8.1, the Amargosa Desert, located within the Alkali Flat-Furnace Creek Ranch subbasin, currently is experiencing overdraft problems. Repository-related ground-water withdrawals probably will not affect the overdrafted areas because of the distance between the overdraft area and well J-13, and the fact that withdrawals are made from different aquifers. Computer models of ground-water flow of Yucca Mountain and vicinity will be developed (Sections 8.3.1.2.2 and 8.3.1.2.3) that can be used to simulate the effects of repository-related withdrawals on the local ground-water system. These models will provide information on the potential for impacts to local ground-water users, the potential impacts from these users to repository water supply, and the possible changes in the ground-water flow direction that might occur as a result of the ground-water withdrawals.

As discussed in Section 3.8.1.4, wells J-12 and J-13, which produce from the welded tuff aquifer, are capable of supplying water for repository activities through decommissioning. If water supply problems in the area were to become more severe, or if pumping wells J-12 and J-13 were to prove to be too costly, an alternate source should be readily available. The information required to fully evaluate the potential for water supply problems, is not available at present. Population projections for the next 50 and 100 yr, and information regarding human settlement patterns will be needed. These data will be obtained and evaluated in the investigations described in Sections 8.3.1.9.2 and 8.3.1.16.2.

The discussions of recharge (Section 3.7.1) and of moisture fluxes in the unsaturated zone at Yucca Mountain (Sections 3.9.3 and 3.9.4) note that the present mean annual precipitation at Yucca Mountain is estimated to be about 150 mm/yr. A knowledge of the historical, present, and probable future precipitation and potential evapotranspiration rates at Yucca Mountain are important in characterizing fully the hydrology of the unsaturated zone. The state of the unsaturated-zone hydrologic system is determined by the rate at which water enters the system as net infiltration across its upper land-surface boundary. Over the Yucca Mountain block as a whole (Sections 3.9.3.4 and 3.9.4), neither the rate nor the areal distribution of net infiltration is presently known. Because the hydrologic system within the unsaturated zone is complexly three-dimensional (Section 3.9.3.4), it is important to establish limiting magnitudes in the rate of net infiltration and its likely spatial distribution. Consequently, as described in Chapter 8.3, an extensive program of in situ infiltration monitoring and evaluation is planned not only to estimate better current rates and distribution, but also to improve understanding of the specific flow mechanisms that control surface infiltration at Yucca Mountain.

The unsaturated zone at Yucca Mountain consists of a stratified sequence of welded and nonwelded, fractured and unfractured tuffs that comprise a fault-bounded, eastward-tilted block extending from 300 to 750 m above the water table (Section 3.9.3.4). The rock-stratigraphic units have been grouped into hydrogeologic units on the basis of common, approximately uniform hydrologic and material properties. The hydrogeologic units comprising the unsaturated zone are divided into three broad categories: (1) densely to moderately welded tuffs, as exemplified by the TCw and TSw units, having low saturated matrix hydraulic conductivity (about 10^{-11} m/s) and high fracture densities (10 to 40 fractures/m^3); (2) nonwelded tuffs, for example, the PTn, and CHn units, having relatively high saturated matrix conductivities (about 10^{-8} to 10^{-6} m/s); and (3) nonwelded, virtually unfractured zeolitized tuffs of low saturated matrix hydraulic conductivity (about 10^{-11} m/s) of which the CHnz unit is the prototype. The repository is proposed to be constructed within rocks in the TSw hydrogeologic unit, which is overlain by the PTn and TCw units and is underlain by the vitric (CHnv) or zeolitic (CHnz) facies of the CHn unit. The water table beneath Yucca Mountain transects the CHn or underlying CFu units beneath almost all of the Yucca Mountain block.

Because of its low matrix hydraulic conductivity, the TSw unit can transmit only small vertical fluxes (less than about 1 mm/yr) at low saturations. However, because of its high fracture density (10 to 40 fractures/m^3), the unit is expected to become more transmissive at or near complete matrix saturation when liquid-water flow within the fractures becomes efficient. The hypothesis is borne out by the results of numerical simulations that were performed on the basis of the unsaturated zone conceptual model and hydrologic-property data. The numerical simulations presume steady-state flow and incorporate approximate, empirically and theoretically derived moisture-characteristics relations for the rock matrix and the fractures. The simulations test three fundamental flow-mechanism hypotheses: (1) that liquid-water flow is restricted predominantly to the rock-matrices in all unsaturated units, (2) that flow occurs predominantly within the fractures of welded TCw and TSw units, and (3) that combined matrix-fracture flow occurs in the TCw and TSw units. The results of these simulations are consistent with the hypothesis that matrix flow is presently dominant within the repository TSw unit for a vertically downward flux of less than 0.5 mm/yr at a matrix saturation of about 0.5, as indicated by presently available data pertaining to ambient conditions within the TSw unit. Flow in fractures and faults may also occur, however, and tests are planned to evaluate this phenomenon (Section 8.3.1.2.3).

The results of preliminary numerical simulations are highly approximate and uncertain because they are based on an overly simplified representation of the hydrologic system and on preliminary hydrologic-property data. Nevertheless, these numerical results are mathematically and physically internally consistent and yield predictions that are consistent quantitatively with the salient features of the conceptual model. Moreover, these results are compatible with the available data concerning ambient hydrologic conditions within the unsaturated zone at Yucca Mountain. There is a need for additional, detailed hydrologic data by which to refine the mathematical model representations. A major concern is to develop an appropriate quantitative description of the flow of liquid water in variably saturated, fractured tuffs. Well established laboratory techniques are available for measuring most matrix hydrologic properties for small rock samples and cores with the possible exceptions of measuring saturated hydraulic conductivity for welded and zeolitized tuff samples. Similar techniques are lacking, however, for single fractures and fracture systems. In fractured media, the scale of measurement must be large compared to the mean fracture aperture and spacing. Hence, the direct empirical determination of the bulk hydrologic properties of the fractured units must rely strongly on hydrologic testing in surface-based boreholes and within the exploratory shaft, as described in Section 8.3.1.2.2. Sufficient data need to be collected to permit statistical analyses of the limits of uncertainty of these data. Uncertainties may be introduced by random errors of measurement, as well as by inherent heterogeneities within the hydrogeologic units. The resulting statistical distributions are needed to provide the requisite input data to stochastic models from which the overall uncertainty of quantitative predictions, such as ground-water travel times, can be assessed.

Ambient hydrologic conditions within the unsaturated zone at Yucca Mountain remain poorly known, although, as described in Chapter 8.3.1.2.2 considerable data on these conditions will be obtained during monitoring in surface-based boreholes and within the exploratory shaft. Preliminary data and inference from test wells USW UZ-1, UZ-6, and H-1 indicate ambient rock-matrix saturations in the range from 0.4 to 0.65 and ambient matric potentials of about -0.3 MPa in the repository TSw unit. These data are consistent with the estimated value of 0.5 mm/yr or less for the present flux through this unit. It may be concluded from these conditions: (1) that the vertical flux of water within the repository TSw unit probably is low; (2) that the flow is restricted largely to the rock matrix with probably little significant flow within fractures; and (3) that the flux may be nearly constant, occurring under unit vertical hydraulic gradient. These conclusions are only indicative of existing conditions; considerably more data need to be acquired before they can be confirmed or refuted with sufficient certainty. Similar conclusions apply for the PTn and TCw units overlying the repository TSw unit; however, for these units, the paucity of reliable data precludes establishing little more than upper limits on possible fluxes based on estimates of the likely rate of net infiltration.

Because of the presence of the natural geothermal gradient, there is the potential for the upward movement of moisture as water vapor within the unsaturated zone. This potential probably is greatest within the fractured TSw unit in which vapor movement is envisioned to occur principally in the partially saturated fractures. Water-vapor movement may occur either as advection superimposed on an underlying bulk-gas flow or as diffusion along the water-vapor concentration gradient that would be coincident with the geothermal gradient if water vapor is in local thermodynamic phase equilibrium with liquid water. Bulk-gas flow may occur either as thermally driven convection or as forced convection impelled by land-surface barometric fluctuations. It is not yet known, however, to what depths the effects of land-surface barometric changes may penetrate and, thus, influence bulk-gas movement within the unsaturated zone. It should be emphasized that until compelling evidence to the contrary becomes available, the hydrologic system within the unsaturated zone beneath Yucca Mountain must be conceived as a two-component (water, air) two-phase (liquid, gas), system involving liquid-water, water-vapor, and bulk-gas movement embedded within the fractured, solid-phase rock matrix. Although virtually no data are available pertaining to the gas-phase hydrologic system, these data are to be collected through gas-phase testing and sampling within surface-based boreholes and the exploratory shaft as described in Chapter 8.3.1.2.2.

Velocity of ground-water flow and resulting travel time in the unsaturated zone strongly depend on effective porosity and hydraulic conductivity of fractures and rock matrix. Based on an upper-bound flux of 0.5 mm/yr, ground-water travel time within the unsaturated zone from the proposed repository to the water table is estimated to range from about 9,000 to 80,000 yr.

The lateral direction of ground-water movement in the saturated zone near the Yucca Mountain site probably is to the southeast. Hydraulic gradient is variable, and southeast of the repository block it is nearly flat. Hydraulic conductivity and effective porosity, two of the parameters that determine ground-water velocities and travel times, are not adequately known yet. Calculations based on conservative values of the controlling parameters indicate that saturated zone ground-water travel time, from the repository block to the accessible environment, may be about 200 yr (Section 3.9.4).

Based on these estimates for travel times, the minimum ground-water travel time from the edge of the repository to the accessible environment under present conditions is approximately 9,200 yr, well in excess of the 1,000 yr limits required by 10 CFR Part 60.113(a)(2).

Uncorrected carbon-14 data indicate that ground water in the vicinity of Yucca Mountain ranges in age from about 10,000 to 20,000 yr, and that waters of either younger or older ages have not been identified. This may bear on ground-water velocities or location of recharge, but the possible implications have not been resolved yet.

Mineralogic evidence suggests that past water levels beneath Yucca Mountain may never have been more than 100 m higher than present levels. Conservative flow modeling of the regional ground-water system suggest that water-table altitudes (past or future) could be, at most, 130 m above present levels, whereas inundation of a repository would require a rise of 200 m or more (Section 3.9.8).

3.10.2 RELATION TO DESIGN

A number of aspects of the ground-water system at Yucca Mountain directly relate to the design of a repository and to waste container design, in particular:

1. Flooding.

2. Ground-water occurrence between the surface and the repository horizon.

3. Ground-water conditions in the waste package environment.

Sections 3.2.2 and 6.2.4 discuss the potential for flooding at the Yucca Mountain site surface facilities. Preliminary investigations discussed in these sections indicate that the surface facilities are located above the level of the probable maximum flood. Further studies are discussed in Section 8.3.1.16. In addition, flood protection measures are included in the design to prevent surficial sheet flow affecting the surface facilities.

The proposed repository at Yucca Mountain is situated in the unsaturated zone. Therefore, it is unlikely that any significant bodies of water would be encountered in the development of the repository. The possibility of the occurrence of perched-water bodies exists; this will be examined during site characterization, particularly through the development of the exploratory shaft. However, it is considered unlikely that even if perched-water bodies do exist between the surface and the repository horizon at Yucca Mountain, they will present a major concern in repository development.

The waste emplacement package environment is one of the more important aspects considered in the design of waste containers. The potential interaction between the container walls and moisture in the emplacement holes is a consideration in estimating the lifetime of the canisters. This aspect is discussed further in Chapter 7, and additional plans for further analyses are presented in Sections 8.3.4 and 8.3.5.

3.10.3 IDENTIFICATION OF INFORMATION NEEDS

As mentioned in the introduction to Chapter 3, the hydrologic system in the vicinity of Yucca Mountain is one of the more important aspects that affects the postclosure and preclosure performance of the proposed repository. In particular, hydrology directly relates to the nine performance issues and associated information needs of Key Issue 1, namely:

<u>Short titles</u>

<u>Issue 1.1</u>: Total system performance (Section 8.3.5.13)

1.1.1 Site information needed for calculations (Section 8.3.5.13.1)

1.1.3 Calculational models for release scenario classes (Section 8.3.5.13.3)

<u>Short titles</u>

1.1.4 Radionuclide releases for scenario classes (Section 8.3.5.13.4)

1.1.5 Probabilistic release estimates (Section 8.3.5.13.5)

Issue 1.2: Individual protection (Section 8.3.5.14)

Issue 1.3: Ground-water protection (Section 8.3.5.15)

1.3.1 Class I or special sources of ground water (Section 8.3.5.15.1)

Issue 1.4: Containment by waste package (Section 8.3.5.9)

1.4.1 Waste package design features needed (Section 8.3.5.9.1)

1.4.3 Scenarios and models needed (Section 8.3.5.9.3)

1.4.4 Containment barrier degradation (Section 8.3.5.9.4)

1.4.5 Time to loss of containment (Section 8.3.5.9.5)

Issue 1.5: Engineered barrier system release rates (Section 8.3.5.10)

1.5.1 Waste package design features (Section 8.3.5.10.1)

1.5.3 Scenarios and models (Section 8.3.5.10.3)

1.5.4 Release rates from waste package and engineered barrier system (Section 8.3.5.10.4)

1.5.5 Radionuclides leaving waste package near-field environment (Section 8.3.5.10.5)

Issue 1.6: Ground-water travel time (Section 8.3.5.12)

1.6.1 Site and design information needed (Section 8.3.5.12.1)

1.6.2 Calculational models to predict travel times (Section 8.3.5.12.2)

1.6.3 Identification of likely travel paths (Section 8.3.5.12.3)

1.6.4 Pre-waste emplacement ground-water travel time (Section 8.3.5.12.4)

1.6.5 Disturbed zone boundary (Section 8.3.5.12.5)

Issue 1.7: Performance confirmation (Section 8.3.5.16)

Issue 1.8: NRC siting criteria (Section 8.3.5.17)

Short titles

Issue 1.9a: Higher-level findings (postclosure) (Section 8.3.5.18)

Issue 1.9b: 100,000-year release (Section 8.3.5.18)

In addition, hydrologic information is needed to satisfy the following postclosure design issues:

Issue 1.10: Waste package characteristics (postclosure) (Section 8.3.4.2)

1.10.4 Near-field environment (Section 8.3.4.2.4)

Issue 1.11: Configuration of underground facilities (postclosure) (Section 8.3.2.2)

1.11.6 Thermal loading and thermomechanical rock response (Section 8.3.2.2.6)

For the postclosure situation, most of the hydrologic information required to satisfy the performance and design issues identified above will be collected by the geohydrology program (Section 8.3.1.2) and its associated investigations:

SCP section	Short title
8.3.1.2.1	Regional hydrology system
8.3.1.2.2	Site unsaturated zone hydrologic system
8.3.1.2.3	Site saturated zone hydrologic system

In addition, Investigation 8.3.1.3.1 will provide information about water chemistry within the potential emplacement horizon and along potential flow paths, and Investigations 8.3.1.5, 8.3.1.6 and 8.3.1.8 will evaluate the potential effects of future climatic conditions, erosion, and igneous and tectonic activity on hydrologic characteristics, respectively.

Investigations 8.3.1.9 and 8.3.1.9.3 provide information on the present and future value of ground-water resources, and the potential effects of exploiting natural resources on the hydrologic characteristics in the vicinity of the Yucca Mountain site.

In the preclosure timeframe, Issues 4.1 and 4.4, along with the hydrology program (8.3.1.16), are associated with hydrologic characteristics, namely:

Issue 4.1: Higher level findings - ease and cost of construction (Section 8.3.5.7)

4.1.1 Site not disqualified (Section 8.3.5.7.1)

4.1.2 Site meets qualifying conditions of technical guidelines (Section 8.3.5.7.2)

4.1.3 Site meets qualifying conditions of system guidelines (Section 8.3.5.7.3)

Issue 4.4: Preclosure design and technical feasibility (Section 8.3.2.5)

4.4.7 Design analyses (Section 8.3.2.5.7)

SCP section	Short title
8.3.1.16.1	Flooding recurrence intervals
8.3.1.16.2	Water supplies
8.3.1.16.3	Ground-water conditions

The plans to collect this information and the methods that will be used to evaluate the effects of the hydrologic regime on performance and design are presented in Section 8.3. The details of each study and activity are presented under each investigation, together with listings of parameters to be collected or that are required, and associated technical procedures and schedules.

3.10.4 RELATION TO REGULATORY GUIDE 4.17

NRC Regulatory Guide 4.17 (NRC, 1987) was used as the basis for the Annotated Outline for Site Characterization Plans. Chapter 3 has been written to satisfy the Annotated Outline and has covered all of the aspects required by Regulatory Guide 4.17, (NRC, 1987) with the following additions:

1. Sections 3.0 and 3.10 have been added to provide an introduction to the material presented in Chapter 3, a summary of the material, and a tie to the material presented in Section 8.3, which discusses the investigations pertinent to hydrology.

2. Sections 3.2.1, 3.5, 3.9.3, 3.9.5 have had title changes from those presented in Regulatory Guide 4.17 to indicate more clearly the material covered in each section.

3. Some fourth order headings presented in Regulatory Guide 4.17 have been deleted because the material requested under each section seemed repetitive. Aside from these minor modifications, all of the material requested by Regulatory Guide 4.17 (NRC, 1987) presently appears in Chapter 3.