modules would increase linearly relative to the increased number of waste packages. Potential impacts of the Proposed Action at groundwater discharge locations in the region depend directly on the fluxes at the Regulatory Compliance Point; therefore, it is reasonable to assume that the cumulative impacts of the inventory modules at the regional discharge locations would also increase by the linear relationship identified in the Repository SEIS. The scale factors for nonradiological contaminants would be likewise. Because the estimated 1-million-year impacts at the discharge locations evaluated in this analysis are all less than or about equal to the dose estimates presented in the Repository SEIS for the Regulatory Compliance Point, the estimated doses at these locations would also be less than or about equal to the estimated doses presented in the Repository SEIS for the inventory modules. Likewise, the intakes of toxic metals would be less than or about equal to those presented in the Repository SEIS.

The Repository SEIS also evaluated the cumulative impact from Nevada Test Site activities, primarily as a result of past underground weapons testing. After evaluation, the estimated total potential cumulative impact (Yucca Mountain impact plus Nevada Test Site impact) would be 0.24 millirem per year to the reasonably maximally exposed individual for the 1-million-year period. It would be reasonable to expect that the same effect applies to the dose impacts estimated in this Analysis of Postclosure Groundwater Impacts for the regional discharge locations, and would therefore contribute an insignificant amount to the 1-million-year dose.

**S.4 Conclusions**

**S.4.1 MAJOR CONCLUSIONS OF THE ANALYSIS**

This Analysis of Postclosure Groundwater Impacts expands the analyses of postclosure impacts from those presented in the Repository SEIS, to include:

- A description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) could leave the flow system;

- An analysis of the cumulative amount of radiological and nonradiological contaminants that could be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time;

- Estimates of contamination in the groundwater, given potential accumulation of radiological and nonradiological contaminants;

- A description of the locations of potential natural discharge of contaminated groundwater for present and expected future, wetter periods;

- A description of the physical processes at the surface discharge locations that could affect accumulation, concentration, and potential remobilization of groundwater-borne contaminants; and

- Estimates of the amount of contaminants that could be deposited at or near the surface;

This analysis provides estimates of health impacts from exposures to contaminants in Amargosa Valley. DOE found that these exposures would result in very small health impacts, which are about the same as those at the Regulatory Compliance Point. This analysis also provides estimates of health impacts from
exposures to contaminants in Death Valley, either from evapotranspiration from the floor of Death Valley or from the springs at Furnace Creek. DOE found that these exposures would be so low that virtually no potential health effects would be expected.

Based on the above, DOE concludes it has provided the information identified by the U.S. Nuclear Regulatory Commission as needed to supplement the Yucca Mountain FEIS and Repository SEIS and, therefore, has adequately addressed impacts on groundwater, or from surface discharges of groundwater, from the proposed repository.

S.4.2 AREAS OF CONTROVERSY

In both the Yucca Mountain FEIS and the Repository SEIS, DOE acknowledged that areas of controversy exist regarding the Proposed Action and the analyses of its impacts. For this Analysis of Postclosure Groundwater Impacts, the Department identified the areas of controversy that are related to postclosure groundwater impacts and are addressed in this document. These areas reflect differing points of view or irreducible uncertainties.

S.4.2.1 Evaluation of the Lower Carbonate Aquifer

The Inyo County Yucca Mountain Repository Assessment Office raised concerns that DOE has not properly evaluated the full extent of the lower carbonate aquifer, the importance of maintaining the upward hydraulic gradient between the lower carbonate aquifer and the volcanic-alluvial aquifer, and the effects of continued or increased pumping on these aquifers. The Department has addressed these concerns in Appendix A.

S.4.2.2 Impacts to Timbisha Shoshone Tribe

As mentioned in Section S.3.3, the Timbisha Shoshone Tribe considers the waters of the Furnace Creek springs to be of traditional and cultural importance and believes that any effects on the purity of these waters would be detrimental to the Tribe’s culture. The analysis DOE included in this document demonstrates that the potential concentrations of contaminants in those springs would be so low that there would be virtually no potential health effects associated with the use of the springs.
1. INTRODUCTION

Spent nuclear fuel and high-level radioactive waste are long-lived, highly radioactive materials that result from certain nuclear activities. For more than 60 years, these materials have accumulated at commercial power plants and DOE facilities and continue to accumulate across the United States. Because of their nature, spent nuclear fuel and high-level radioactive waste must be isolated from the human environment, and monitored for long periods. The United States has focused a national effort on the siting and development of a geologic repository for disposal of these materials and on the development of systems for transportation of the materials safely from their present storage locations to the repository. Through the passage of the Nuclear Waste Policy Act, as amended (NWPA) (42 U.S.C. 10101 et seq., 1987), Congress found that:

- The Federal Government has the responsibility to provide for the permanent disposal of high-level radioactive waste and spent nuclear fuel to protect the public health and safety and the environment.

- Appropriate precautions must be taken to ensure that these materials do not adversely affect the public health and safety and the environment for this or future generations.

The NWPA directed that the U.S. Department of Energy (DOE or the Department) evaluate the Yucca Mountain site in Nye County, Nevada as a potential location for a geologic repository. In addition, in 2002, Congress and the President designated the Yucca Mountain site for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel (Public Law 107-200; 116 Stat. 735). A geologic repository for spent nuclear fuel and high-level radioactive waste would permanently isolate radioactive materials in a deep subsurface location to limit risk to the health and safety of the public.

1.1 Background

DOE completed the Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada (DOE/EIS-0250F; DIRS 155970-DOE 2002, all) (Yucca Mountain FEIS) in February 2002. The Proposed Action addressed in the FEIS is to construct, operate and monitor, and eventually close a geologic repository at Yucca Mountain in southern Nevada for the disposal of spent nuclear fuel and high-level radioactive waste. The Yucca Mountain FEIS considered the potential environmental impacts of a repository design for surface and subsurface facilities; a range of canister packaging scenarios, repository thermal operating modes, and repository sizes; and plans for the construction, operation, monitoring, and eventual closure of the repository. In addition, the FEIS examined various national transportation scenarios and Nevada transportation alternatives for shipment of spent nuclear fuel and high-level radioactive waste to the repository.

In June 2008, DOE issued the Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS). The basic elements of the Proposed Action evaluated in the Repository SEIS did not change from that evaluated in the Yucca Mountain FEIS. As described in the Repository SEIS, the surface and subsurface facilities would allow DOE to operate the repository following a primarily canistered approach in which most
commercial spent nuclear fuel would be packaged at the reactor sites in transportation, aging, and disposal (TAD) canisters. DOE would repackage any commercial spent nuclear fuel that arrived at the repository in packages other than TAD canisters in TAD canisters. The Department would construct the surface and subsurface facilities over a period of several years (referred to as phased construction) to accommodate an increase in spent nuclear fuel and high-level radioactive waste receipt rates as repository operational capability reached its design capacity. The Repository SEIS evaluated potential environmental impacts of the repository design and operational plans as described in the application that DOE submitted on June 3, 2008, to the U.S. Nuclear Regulatory Commission (NRC) seeking authorization to construct the repository, as required in Section 114(b) of the NWPA (DIRS 185814-DOE 2008, all).

On September 8, 2008, the NRC issued a Notice of Acceptance (letter) to the Department (DIRS 186112-Weber 2008, all) informing that the license application had been accepted for docketing. Included with this notice was the U.S. Nuclear Regulatory Commission Staff’s Adoption Determination Report for the U.S. Department of Energy’s Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain (DIRS 186113-NRC 2008, all) (NRC staff’s Adoption Report), dated September 5, 2008 (http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/nrc-eis-adr.pdf). The NRC staff’s Adoption Report describes the review the NRC staff conducted to determine if it was practicable to adopt the EISs in accordance with 10 CFR 51.109. The NRC staff concluded that it was practicable to adopt the Yucca Mountain FEIS and supplements prepared by DOE, but that additional supplementation was needed to address the potential impacts of the proposed action on groundwater and from surface discharges of groundwater (the basis for the NRC staff’s position is contained in the NRC staff’s Adoption Report and summarized in Section 1.2 of this chapter). In the letter, the NRC staff requested that DOE provide a plan for the preparation of a supplement to the Yucca Mountain FEIS and supplements within 30 days.

On October 3, 2008, DOE informed the NRC that it planned to supplement the Yucca Mountain FEIS and supplements as discussed in the enclosure to the NRC letter of September 8, 2008. Accordingly, on October 24, 2008, DOE published a Notice of Intent to prepare a Postclosure Groundwater SEIS and invited comments on the notice (73 FR 63463). In its Notice, DOE described the scope of its analysis:

The requested supplement will analyze further the repository-related impacts on groundwater, and from surface discharges of groundwater. More specifically, the supplement will describe the extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system. In addition, the supplement will provide an analysis of the cumulative amount of radiological and non-radiological contaminants that can be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time. This information will be used to estimate contamination in the groundwater, given potential accumulation of radiological and non-radiological contaminants.

The supplement also will provide a discussion of the impacts on soils and surface materials from the processes involved in surface discharges of contaminated groundwater. A description of locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods will be included, as will a description of the physical processes at surface discharge locations that can affect accumulation, concentration, and potential remobilization of groundwater-borne
contaminants. This information will be used to develop estimates of the amount of contaminants that could be deposited at or near the surface, and potential environmental impacts.

In the Notice of Intent, DOE announced a 30-day public comment period, which ended on November 24, 2008. During the 30-day period, DOE received comments from: (1) the Inyo County Yucca Mountain Repository Assessment Office, (2) the Lincoln County Board of County Commissioners, (3) the White Pine County Nuclear Waste Project Office, and (4) the Timbisha Shoshone Tribe. The primary nature of the comments focused on the following:

- Inyo County – requested expansion and/or refinement of the scope of the supplement as defined by the NRC staff. Specifically, the County requests that DOE evaluate perceived flaws in the model used to analyze long-term performance, impacts from continued regional groundwater pumping, impacts to endangered species in springs in Death Valley, and that DOE address cleanup and remediation measures.

- Lincoln County – requested an expansion of the scope of the supplement to include an additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in counties northeast of Yucca Mountain.

- White Pine County – requested an expansion of the scope of the supplement to include an additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in counties northeast of Yucca Mountain.

- Timbisha Shoshone Tribe – requested that the supplement include analyses of several topics related to groundwater flow, potential transport of nuclear waste, and possible effects in Death Valley National Monument.

DOE has since decided not to supplement the Yucca Mountain FEIS and its supplements, but rather to prepare this Analysis of Postclosure Groundwater Impacts for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada (Analysis of Postclosure Groundwater Impacts). The Analysis of Postclosure Groundwater Impacts addresses the information identified by the NRC staff as needed to supplement DOE’s EISs and supplements, and the comments received on the Notice of Intent. The comment documents and DOE’s response to these comments are provided as Appendix A to this document.

### 1.2 Scope of the Postclosure Groundwater Impact Analysis

This Analysis of Postclosure Groundwater Impacts addresses the information identified by the NRC staff as needed to supplement DOE’s EISs. Specifically, the NRC staff’s Adoption Report identified two areas that needed supplementation, as quoted below (DIRS 186113-NRC 2008, Section 3.2.1.4.2.2, pp. 3-10 through 3-12):
Need for Supplementation 1: Impacts on Groundwater

The EISs have not provided complete and adequate discussion of the nature and extent of the repository’s cumulative impact on groundwater in the volcanic-alluvial aquifer. A supplement should include the following information:

- A description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system. For example, the DOE license application describes potential groundwater flow farther to the south of Alkali Flats, into the Southern Death Valley subregion of the regional model domain (DOE, 2008a, General Information, Section 5.2.2.2). This component of the groundwater flow system is not discussed in the EISs.

- An analysis of the cumulative amount of radiological and non-radiological contaminants that can be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time. In its license application, for example, DOE provides calculated cumulative releases of some radionuclides at different stages within the repository system, as intermediate results in TSPA (e.g., DOE, 2008a, Safety Analysis Report, Section 2.4.2.2.3). This type of information, for radiological and non-radiological contaminants, could be used in the analysis.

- Estimates of contamination in the groundwater, given potential accumulation of radiological and non-radiological contaminants. One way to analyze the overall impacts on groundwater may be a mass-balance approach that accounts for mass released, the part of the groundwater flow system affected by potential releases, and the expected processes that could affect released contaminants. Such an approach would also show the extent of contamination and possible impacts on water quality.

Need for Supplementation 2: Impacts from Surface Discharges of Groundwater

The EISs have not provided a complete and adequate discussion of the impacts on soils and surface materials from the processes involved in surface discharges of contaminated groundwater. A supplement should include the following additional information:

- A description of the locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods (for example, as discussed in DOE, 2008a, Safety Analysis Report, Section 2.3.1.2).

- A description of the physical processes at the surface discharge locations that can affect accumulation, concentration, and potential remobilization of groundwater-borne contaminants.

- Estimates of the amount of contaminants that could be deposited at or near the surface. This involves estimates of the amount of groundwater involved in discharge or near-surface evaporation, the amounts of radiological and non-radiological
contaminants in that water, contaminant concentrations in the resulting deposits, and potential environmental impacts (e.g., effects on biota).

1.3 Document Organization and Contents

This Analysis of Postclosure Groundwater Impacts is organized to address the needs identified in the previous section. Chapter 2 provides descriptions of the volcanic-alluvial aquifer including the current groundwater flow system and evidence of past climates and associated flow systems. Further, Chapter 2 provides summary information from the modeling of the groundwater flow system and how the Repository SEIS and the Yucca Mountain Repository License Application (DIRS 185814-DOE 2008, all) used that modeling.

Chapter 3 of this Analysis of Postclosure Groundwater Impacts presents the analytical methodology and results for the estimation of impacts from contaminated groundwater and surface discharges in the accessible environment. Chapter 3 also includes a discussion of potential postclosure impacts to American Indians in the Death Valley region.

Appendix A of this analysis presents the comment documents received after DOE’s publication of the notice of intent to prepare the SEIS, and DOE’s responses to those comments. Appendix B provides analytical details that support the results provided in Chapter 3.

REFERENCES


Introduction and Background Information


2. AFFECTED ENVIRONMENT

This chapter presents baseline environmental conditions associated with the supplemental evaluation needs posed by U.S. Nuclear Regulatory Commission (NRC) staff in the U.S. Nuclear Regulatory Commission Staff’s Adoption Determination Report for the U.S. Department of Energy’s Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain (NRC staff’s Adoption Report) (DIRS 186113-NRC 2008, all). The topical areas identified by NRC staff include elements of baseline environmental conditions as well as additional impact evaluations. The supplemental environmental conditions identified in the NRC staff’s Adoption Report are: (1) a description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system; and (2) a description of the locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods. Chapter 1 of this Analysis of Postclosure Groundwater Impacts provides more information about the NRC staff’s requests. The scope of this chapter is to provide the supplemental information on baseline environmental conditions and to provide information needed to understand the supplemental impact evaluations presented in Chapter 3 of this analysis.

The environmental conditions described in this chapter and the impact evaluations of Chapter 3 are supplemental to those presented in the Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada (DOE/EIS-0250F; DIRS 155970-DOE 2002, all) (Yucca Mountain FEIS) and the Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS) for the long-term performance of the proposed repository at Yucca Mountain. In order to support the impact evaluations in Chapter 3, this chapter includes the following additional descriptive information on the affected environment:

- A description of the current groundwater flow system, addressing each of the groundwater basins or sections through which groundwater from beneath Yucca Mountain could pass. The basin or section descriptions include identification of the aquifers, locations of natural discharge, and direction of subsurface flow.

- A discussion of past (ancient) climates and hydrological conditions that provide the basis for possible future conditions as addressed in the Yucca Mountain FEIS, Repository SEIS, and in Chapter 3 of this analysis.

- A description of the numerical modeling performed to simulate the regional groundwater flow system for past, present, and future climate conditions.

- A discussion of the groundwater modeling performed in the local area of Yucca Mountain and the associated evaluations of impact for the reasonably maximally exposed individual (RMEI) as was presented in the Repository SEIS. This discussion, along with the descriptions of the regional flow system modeling efforts, provides the basis for the current modeling and evaluation approach described in Chapter 3 of this analysis, which evaluates potential contaminant flow paths and potential impacts beyond the RMEI location.
2.1 Current Groundwater Flow System

This section presents general information on the Death Valley regional groundwater flow system, illustrated in Figure 2-1, which is then followed by more specific detail on the portions of the regional flow system that the proposed repository at Yucca Mountain could affect.

In the late 1990s, DOE directed the U.S. Geological Survey (USGS) to improve its groundwater flow model of the Death Valley regional flow system to support DOE programs at the Nevada Test Site and Yucca Mountain. The results of the USGS’s work are presented in Death Valley Regional Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model (DIRS 173179-Belcher 2004, all), and much of the information in this section comes from that document.

The USGS technical report presents a hydrologic conceptual model of the groundwater flow system within the Death Valley region as well as a description of the construction of a computer-based numerical model to simulate that flow system. The conceptual model is an interpretation or working description of how the flow system works. It was developed based on data that had been measured (such as water table elevations), calculated (for instance, estimates of recharge and discharge), or otherwise collected (such as groundwater hydrochemistry characteristics) to represent the regional flow system. The numerical model was then developed to simulate flow in the regional system and provide additional information. The flow paths for groundwater from beneath Yucca Mountain are contained within the flow system boundaries of the numerical model. The information presented in this section, unless specifically noted as coming from the numerical model, is based on the conceptual model of the Death Valley regional groundwater flow system. Modeling results are left primarily for discussion in Chapter 3.

The source of groundwater flow in the region is predominantly from recharge due to infiltration of precipitation that falls within the boundaries, and most of the recharge originates in the mountainous areas. The major recharge areas include: (1) along the eastern boundary (the Timbahaute, Pahranagut, and Sheep ranges and the Spring Mountains); (2) along the western part of the boundary (Panamint Range and the Cottonwood Mountains); (3) the northern area of the Nevada Test Site (Kawich and Belted ranges and Rainier Mesa), and (4) along the eastern margin of Death Valley (Grapevine and Funeral mountains) (DIRS 173179-Belcher 2004, pp. 117 and 118). Areas of recharge are generally reflected by mounds in the water table or potentiometric surface, and the largest mound in the region is associated with the Spring Mountains (DIRS 169734-BSC 2004, pp. 8-9 and 8-10), located southeast of Yucca Mountain.

Water also enters the regional flow system as throughflow from adjoining groundwater basins, predominantly from the north, west, and south, but the amount of water coming into the system laterally is estimated to be relatively small (roughly 10 percent) in comparison with that coming in as recharge from the surface (DIRS 173179-Belcher 2004, pp. 330 and 331; DIRS 169734-BSC 2004, p. 8-42).
Figure 2-1. Boundaries and prominent topographic features of the Death Valley regional groundwater flow system.
One can conceptualize groundwater flow in the region as including a set of relatively shallow, localized flow systems superimposed on deeper intermediate and regional flow systems. A localized flow system can be visualized as consisting of a single basin or valley between mountain ridges; an intermediate flow system would be at a greater depth, supporting flow beneath two or more valleys. The overall direction of groundwater movement is from the source areas (that is, those primary areas of recharge generally near the margins of the regional flow system) toward the regional hydrologic sink (that is, the area to which groundwater flows) in the floor of Death Valley.

The largest volume of groundwater loss in the region is also in Death Valley in the form of spring discharges and evapotranspiration. In this discussion, sites of evapotranspiration losses are locations where groundwater is naturally at or close enough to the surface of the ground to be susceptible to evaporation or uptake by plants. Losses from pumping and subsequent use of the water are identified separately. There are numerous additional discharge locations along flow paths toward Death Valley. By volume of water lost, the largest of these is represented by the spring discharges and evapotranspiration at Ash Meadows. Other areas of notable water loss (all by evapotranspiration and occasionally with spring discharges) include Sarcobatus Flat, Oasis Valley, Pahrump Valley, and Tecopa Basin (DIRS 173179-Belcher 2004, pp. 330 and 331). As with water coming laterally into the regional flow system, there is throughflow that leaves the system laterally into adjoining groundwater systems. Again, the amount of water that leaves the regional flow system in this manner, primarily along the east and southeast boundaries, is estimated to be relatively small (less than 10 percent) in comparison with the volume lost within the boundaries (DIRS 173179-Belcher 2004, pp. 330 and 331; DIRS 169734-BSC 2004, p. 8-42).

Another pertinent factor in describing the general nature of groundwater in the regional flow system is the nature of the geologic material through which it passes. The eastern and southern parts of the region lie within the carbonate-rock province of the Great Basin, which is characterized by thick sequences of carbonate rock. The northwest part of the region generally is underlain by volcanic rocks that are part of the southwest Nevada volcanic field (DIRS 169734-BSC 2004, p. 8-4). In characterizing this region, the USGS identified 25 different hydrogeologic units in five different groupings that begin with the youngest unconsolidated Cenozoic basin-fill (or alluvial) deposits along with younger volcanic rocks. The groupings then incorporate the consolidated Cenozoic basin-fill deposits; the Cenozoic volcanic rocks of the southwestern Nevada volcanic field; the Mesozoic, Paleozoic, and late Proterozoic sedimentary rocks (including the carbonate rock); and finally the lowest units, the crystalline metamorphic rocks of the Proterozoic Era and the intrusive rocks of all ages. Units within these groupings can be aquifers or confining units. A confining unit is a rock or sediment unit of relatively low permeability that retards the movement of water in or out of adjacent aquifers, whereas an aquifer is a permeable water-bearing unit of rock or sediment that yields water in a usable quantity to a well or spring. Within the 25 hydrogeologic units, the USGS characterized 9 as aquifers, 8 as confining units, and another 8 as units that can function either as aquifers or confining units. It is noted that these are general characterizations because the hydrogeologic units vary in material and hydraulic properties over the extent of the regional groundwater flow system (DIRS 173179-Belcher 2004, pp. 39 and 40), which is the reason some units are identified as either aquifers or confining units.

Simplifying the hydrogeologic units presented in the USGS model (and in almost any other groundwater study of the region), the principal aquifers of the region can be characterized as basin-fill (or alluvial),
Affected Environment

volcanic, and carbonate. The basin-fill is the eroded, or otherwise broken down material deposited in between mountains and ridges. These bodies of sand, silt, gravel, and other materials can be very thick, and when they extend below the water table, permeable portions serve as aquifers. *Volcanic aquifers* are in permeable units of igneous rock (of volcanic origin), and *carbonate aquifers* are in permeable units of limestone or dolomite (carbonate rock). (The carbonate aquifer is more appropriately termed the carbonate-rock aquifer, but this document refers to it as simply the carbonate aquifer and uses “carbonate rock” to reference the geologic strata.) Consistent with the location of the southwest Nevada volcanic field identified previously, the mountainous area of the north-central portion of the Death Valley region is often underlain by volcanic rocks and the associated volcanic aquifers. Consistent with the location of the carbonate-rock province of the Great Basin, carbonate aquifers are regionally extensive, particularly in the east and southern portions of the region, and are often at great depths below volcanic and *alluvial aquifers*. When all three aquifers are present, the volcanic rocks are generally in hydraulic connection with the overlying basin-fill and may be in hydraulic connection with underlying carbonate rocks as well as laterally from one basin to another (DIRS 169734-BSC 2004, p. 8-4). It should be noted that two carbonate aquifers are recognized in the region: the *upper* and *lower carbonate aquifers*. The upper unit is generally only of local importance (that is, it is not significant in the regional flow system) and is not present in the flow path from Yucca Mountain, and, accordingly, is not discussed further.

The regional flow system is divided into subregions, basins, and sections to facilitate discussion and delineate general areas of groundwater recharge, discharge, and movement within the boundaries of the overall flow system. Within the region (Figure 2-1) are the northern *Death Valley subregion*, the central Death Valley subregion, and the southern Death Valley subregion. The regional flow system is divided into these subregions for descriptive purposes only, with delineation of the subregion boundaries based on several different physical attributes including discharge locations in Death Valley. Recharge entering the system at Yucca Mountain would be within the central Death Valley subregion and, based on the primary discharge locations within that subregion, will likely never leave it as groundwater. The focus of the discussion in this Analysis of Postclosure Groundwater Impacts is, therefore, the central Death Valley subregion; specifically, that portion of the subregion that contains the groundwater flow paths from Yucca Mountain. This discussion includes the southern Death Valley subregion because it is possible that some throughflow, including flow paths from Yucca Mountain, occurs between the central and southern subregions. Flow paths from Yucca Mountain do not extend toward the northern Death Valley subregion, but throughflow from the northern subregion into the central subregion does occur.

The subsections that follow begin with descriptions of the applicable subregions and provide a broad view of the overall subregion before moving to the discussion of the applicable basin, the next category down in the hierarchy used to define the flow system. Similarly, the basin is discussed in broad terms before focusing on the applicable groundwater section, the lowest category in the hierarchy. In this manner, each of the groundwater sections through which groundwater from Yucca Mountain could pass is addressed beginning beneath Yucca Mountain and following the general flow path to the low point of the regional flow system, which is Death Valley. Death Valley extends in a northwest-to-southeast direction across all three of the subregions (that is, the northern, central, and southern Death Valley subregions). The lowest area of Death Valley, Badwater Basin, is within the central Death Valley subregion.

Defining the Death Valley regional groundwater flow system included estimating the amount of water moving through the system. In most cases, the USGS’s technical report (DIRS 173179-Belcher 2004, all) presents this information in the form of estimates of quantities of water lost from the system through spring discharges, evapotranspiration, and pumping. Thus the report does not generally provide estimates
for quantities of groundwater moving through any specific location within the flow system. However, if it is assumed that the system is reasonably in balance (that is, there are no areas where reservoirs of surface or subsurface water are growing or being depleted), then the estimates of water losses along the flow paths provide an indication of at least the minimum amount of groundwater that is moving along those flow paths. It is recognized that some portions of the regional system are currently not in balance (for example, as indicated by lowered water levels in some areas due to pumping), but the water loss values are still of use in describing the movement in the system. Table 2-1 provides estimates of water losses along the sections of the regional flow system that are described in the discussions that follow. That is, the table presents information for those sections of the flow system that could involve flow paths for groundwater that originates beneath Yucca Mountain. The USGS’s technical report identifies and describes numerous other significant areas of the flow system where groundwater is lost from the system, which are not included in Table 2-1 since they are not applicable to the analysis in this Analysis of Postclosure Groundwater Impacts.

Table 2-1. Estimates of water losses along select sections of the regional flow system.

<table>
<thead>
<tr>
<th>Flow path section</th>
<th>Annual groundwater losses/discharges (acre-feet)</th>
<th>Specific spring discharges(^a)</th>
<th>Losses from evapotranspiration(^b)</th>
<th>Groundwater pumping in 2003(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Death Valley subregion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkali Flat – Furnace Creek basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fortymile Canyon section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amargosa River section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Funeral Mountains section</td>
<td>2,300(^e)</td>
<td>1,350(^d)</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Southern Death Valley subregion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoshone – Tecopa section</td>
<td>2,530(^g)</td>
<td>27(^h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California Valley section</td>
<td>6,400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ibex Hills section</td>
<td>3,420(^i)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: To convert acre-feet to cubic meters, multiply by 1,233.49.


\(^c\) Source: DIRS 185968-Moreo and Justet 2008, database.

\(^d\) Evapotranspiration losses from the Amargosa River section include those from the Franklin Well area and those from the Alkali Flat (also known as Franklin Lake Playa) area.

\(^e\) The spring discharge shown for the Funeral Mountains section is the total for the Texas, Travertine, and Nevares springs. The data source describes the discharge value for Travertine Springs (1,370 acre-feet per year) as being the total of 10 springs in the same area, and the discharge for Nevares Spring (560 acre-feet per year) is described as including nearby Cow and Salt springs.

\(^f\) The evapotranspiration loss shown for the Funeral Mountains section is the total annual loss from the following areas (from north to south): Cottonball Basin (3,030 acre-feet per year), Furnace Creek Ranch (3,410 acre-feet per year), Middle Basin (1,960 acre-feet per year), Badwater Basin (5,950 acre-feet per year), west side vegetation (5,390 acre-feet per year), and Mormon Point (3,950 acre-feet per year).

\(^g\) Evapotranspiration losses from the Shoshone – Tecopa section include those from areas along the Amargosa River bed and those from the Chicago Valley playa.

\(^h\) The groundwater pumpage volume for the Shoshone – Tecopa section includes pumpage from the California Valley section. The data source does not provide a breakdown of the two sections.

\(^i\) The evapotranspiration loss shown for the Ibex Hills section is the total annual loss from the following areas (from north to south): Confidence Mill site (960 acre-feet per year) and Saratoga Springs (2,460 acre-feet per year).
Figure 2-2. Central Death Valley subregion of the Death Valley regional groundwater flow system.
2.1.1 CENTRAL DEATH VALLEY SUBREGION

The central Death Valley subregion (Figure 2-2) is divided into three basins: (1) the Pahute Mesa – Oasis Valley groundwater basin, which incorporates northern and northwestern portions of the subregion; (2) the Ash Meadows groundwater basin, which consists of the east portion of the subregion; and (3) the Alkali Flat – Furnace Creek groundwater basin, located in the central area of the subregion between the other two basins and extending to the south-southwest. In general terms, groundwater in the first two basins flows southward (and to the southwest in the case of the Ash Meadows groundwater basin), contributing flow to the Alkali Flat – Furnace Creek groundwater basin. Conversely, groundwater in the Alkali Flat – Furnace Creek basin does not move into either of the other two basins of the Central Death Valley subregion.

The three basins of the central Death Valley subregion were named based on major discharge areas. As Figure 2-2 shows, groundwater flow in the Pahute Mesa – Oasis Valley basin is generally toward an area having spring discharges and evapotranspiration losses in Oasis Valley near Beatty. Some of the flow may also go west toward Sarcobatus Flat in the northern Death Valley subregion, and some may flow to the east toward Crater Flat. Finally, groundwater not discharging within Oasis Valley flows through the thin layer of alluvium or the low-permeability basement rocks at Amargosa Narrows and into the Alkali Flat – Furnace Creek basin (DIRS 173179-Belcher 2004, p. 150).

Groundwater flow in the Ash Meadows basin, the largest of the basins in the central Death Valley subregion, generally moves toward the discharge area of Ash Meadows. In Ash Meadows, groundwater encounters a northwest-to-southeast trending fault where water coming in primarily from the east in the lower carbonate aquifer hits less permeable fine-grained basin-fill sediments. The result is about 30 springs along a 16-kilometer (10-mile) long spring line that generally follows the trace of the fault (DIRS 173179-Belcher 2004, p. 152). Although earlier conceptual models of the Ash Meadows basin had much of the flow at Ash Meadows originating in Pahranagat Valley, more recent evidence suggests that most, if not all, of the water discharging at Ash Meadows originated in the Spring Mountains. Most of the discharged water likely infiltrates and recharges the alluvial aquifers, with much of this discharging as evapotranspiration along the Amargosa River, Carson Slough, and Alkali Flat (DIRS 173179-Belcher 2004, p. 152), located just to the south-southwest of Ash Meadows. (Alkali Flat is also referred to as Franklin Lake Playa.)

Yucca Mountain and water infiltrating through the area of the proposed Yucca Mountain Repository are within the Alkali Flat – Furnace Creek basin. Since groundwater in this basin does not contribute flow to either of the other two basins in the central Death Valley subregion, and because of the significance of this basin with respect to groundwater flow from the proposed repository, the remaining discussion of this subregion is limited to the Alkali Flat – Furnace Creek basin.

2.1.1.1 Alkali Flat – Furnace Creek Groundwater Basin

The northern boundary of the Alkali Flat – Furnace Creek groundwater basin is in the area of Pahute Mesa in the central area of the regional flow system. The basin extends to the southwest, encompassing Fortymile Canyon, Crater Flat, the Amargosa Desert, the Funeral Mountains, the central portion of Death Valley, and the eastern slope of the Panamint Range (on the west side of Death Valley) (Figure 2-2). Groundwater in the basin moves through volcanic aquifers in the north and alluvial and carbonate
affected Environment

aquifers in the south. As with the regional flow system in general, the direction of flow is toward the regional sink of Death Valley.

The primary recharge areas for the Alkali Flat – Furnace Creek basin are Pahute Mesa and the Timber and Shoshone mountains in the north, the Grapevine and Funeral mountains (separating Amargosa Desert from Death Valley) in the center, and the Panamint Range on the southwestern boundary. Additional water sources for the Alkali Flat – Furnace Creek basin are in the form of groundwater throughflow, possibly from the Sarcobatus Flat and Oasis Valley areas in the north and from the Ash Meadows area in the east.

The main surface discharge area in the basin is the springs in Death Valley, specifically those in the Furnace Creek area, including the Texas Springs, Travertine Springs, and Nevares Springs. The largest losses in the basin, however, are attributed to evapotranspiration losses over the floor of Death Valley. In the south-central part of the basin, near the Nevada-California border, there are also discharge areas along the Amargosa River, Carson Slough, and Alkali Flat. Throughflow may also result in groundwater leaving the basin and entering the southern Death Valley subregion by following the general course of the Amargosa River past Alkali Flat and through a veneer of alluvium near Eagle Mountain.

The Yucca Mountain FEIS described the flow in the alluvial aquifer of the southern Amargosa Desert as moving toward the primary discharge area of Alkali Flat, with a small portion potentially moving toward the springs in the Furnace Creek area of Death Valley (DIRS 155970-DOE 2002, pp. 3-40 and 3-46). The subsequent Repository SEIS also described the predominant flow in the alluvial aquifer of the southern Amargosa Desert as moving toward Alkali Flat, but the SEIS cited more recent studies as showing evidence that a portion of the flow likely goes to the Furnace Creek area, with some minor amounts also potentially going beyond Alkali Flat and following the general course of the Amargosa River into Death Valley (DIRS 180751-DOE 2008, pp. 3-34 and 3-35). These are relatively minor changes in the conceptual model of the groundwater flow system in the Amargosa Desert. However, this Analysis of Postclosure Groundwater Impacts reaches different conclusions about the direction of flow. As Chapter 3 of this analysis describes, DOE used the Death Valley regional flow system model to simulate flow conditions in the absence of any significant pumping in the region, so the simulation included no effects from pumping in the Amargosa Desert on flow paths from Yucca Mountain. Results of the simulation for this no-pumping scenario show flow paths from Yucca Mountain going primarily toward the Furnace Creek area and the floor of Death Valley beyond, with only a small portion going to Alkali Flat. Although the Death Valley regional groundwater flow system model is considered the best representation of the regional flow system developed to date, there are still uncertainties inherent in its use. Since the model predicts a portion (albeit small) of the flow going to Alkali Flat, it does not preclude that flow path as a possibility. Further, groundwater reaching as far south as Alkali Flat might, under at least some conditions, continue southward into the southern Death Valley subregion. As a result, even though the modeling scenario in this case predicts a dominant flow path toward the Furnace Creek area, the conceptual model for purposes of this evaluation conservatively continues to identify other possible flow paths to the south, toward Alkali Flat and beyond.

The Alkali Flat – Furnace Creek basin is divided into four sections (identified by their numbers in Figure 2-2): (3a) Fortymile Canyon, (3b) Amargosa River, (3c) Crater Flat, and (3d) Funeral Mountains. The proposed repository at Yucca Mountain would be located within the Fortymile Canyon section, and the natural groundwater flow path from beneath the repository is from that section to the Amargosa River section. In the southern portion of the Amargosa River section, groundwater moves to the west to
discharge points in the Funeral Mountains section, further south to discharge in the area of Alkali Flat, or past Alkali Flat into the southern Death Valley subregion. The following sections describe in more detail the groundwater pathway from the Yucca Mountain area.

Table 2-2 provides a summary of the sample results from a series of water quality samples collected from springs in the Furnace Creek area and from wells in the Amargosa Farms area. These are primary areas of impact Chapter 3 evaluates, so the data are presented here to provide an indication of the baseline condition of groundwater in these two areas. The table also shows drinking water standards for comparison purposes. It is recognized that these samples represent groundwater and were not collected from drinking water systems, so the standards are not directly applicable. However, the standards do provide a recognized benchmark. As can be seen in Table 2-2, with the exception of arsenic in three locations, and lead and fluoride in one location (indicated by shading in the table), the groundwater samples represent water of good quality. Relatively high concentrations of natural arsenic are a recognized problem for groundwater in this area, and since the U.S. Environmental Protection Agency (EPA) lowered the drinking water standard from 0.05 to 0.01 milligrams per liter in 2006, many of the groundwater sources in the area exceed the standard.

2.1.1.1.1 Fortymile Canyon Section

Recharge and Movement
Recharge and throughflow from volcanic rocks of the eastern Pahute Mesa and the western part of Rainier Mesa are the sources for groundwater flow in the Fortymile Canyon section. Infiltration of runoff in the upper reaches of Fortymile Canyon and Fortymile Wash during moderate to intense precipitation events may also be a significant source of recharge in the section (DIRS 173179-Belcher 2004, p. 152). The amount of water infiltrating at Yucca Mountain is small in comparison with these other areas and is not a significant contributor to recharge. Infiltrating water at Yucca Mountain that reaches the saturated zone reaches a volcanic aquifer. As indicated in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-42), the saturated zone at Yucca Mountain is roughly 300 meters (980 feet) below the level of the repository. The lower carbonate aquifer is also present beneath the repository site, but it is more than 1,250 meters (4,100 feet) below the repository level (DIRS 180751-DOE 2008, p. 3-42). Thus, there is about 950 meters (3,100 feet) between the top of the saturated zone, or water table, and the top of the lower carbonate aquifer. As noted in the Repository SEIS, a well (well UE-25 p-1) completed to the lower carbonate aquifer at Yucca Mountain indicated a water level, or potentiometric head, in that aquifer about 20 meters (66 feet) higher than the water level in the overlying volcanic aquifer. This demonstrates an upward hydraulic gradient between the lower carbonate aquifer and the volcanic aquifer at this location. The upward gradient, along with the great depth and the intervening confining unit(s), which hinder flow between the aquifers and allow the upward gradient to exist, affects the movement of groundwater in this area. Infiltrating water (and potential releases from the repository) that reached the saturated zone in this area would remain in the overlying volcanic aquifer and move laterally rather than down into the lower carbonate aquifer. (Note: Under natural conditions, a separating confining unit or a zone of low permeability would generally be necessary for an upward hydraulic gradient to exist between a low aquifer and an overlying aquifer, otherwise the heads in the aquifers would equalize.) At Yucca Mountain, the groundwater in the volcanic aquifer flows to the southeast. This condition is localized, in that by the time the flow reaches the Fortymile Wash area, the general direction of flow shifts to the south and into the Amargosa River section.
**Table 2-2.** Water quality of springs in the Furnace Creek area and of wells in the Amargosa Farms area.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Units</th>
<th>Drinking water standard</th>
<th>Select springs of the Furnace Creek area&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Select wells of the Amargosa Farms area&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Navel Spring&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Texas Spring&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of observations</td>
<td>2 to 3 1 to 4</td>
</tr>
<tr>
<td><strong>Inorganics</strong></td>
<td></td>
<td></td>
<td>1 to 4</td>
<td>1</td>
</tr>
<tr>
<td>Arsenic</td>
<td>mg/L</td>
<td>0.010</td>
<td>Not analyzed</td>
<td>0.024</td>
</tr>
<tr>
<td>Barium</td>
<td>mg/L</td>
<td>2</td>
<td>0.032</td>
<td>0.039&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Beryllium</td>
<td>mg/L</td>
<td>0.004</td>
<td>Not analyzed</td>
<td>(0.003)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cadmium</td>
<td>mg/L</td>
<td>0.005</td>
<td>(0.01)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0038&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Chloride (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>250&lt;sup&gt;f&lt;/sup&gt;</td>
<td>75&lt;sup&gt;c&lt;/sup&gt;</td>
<td>37.3</td>
</tr>
<tr>
<td>Chromium (total)</td>
<td>mg/L</td>
<td>0.1</td>
<td>0.0035</td>
<td>0.00075&lt;sup&gt;r&lt;/sup&gt;</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/L</td>
<td>1.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(0.01)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0083&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fluoride</td>
<td>mg/L</td>
<td>4.0</td>
<td>1.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Iron (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>0.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.098&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0039&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lead</td>
<td>mg/L</td>
<td>0.015&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(0.10)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.038&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Manganese (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(0.001)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0016&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mercury</td>
<td>mg/L</td>
<td>0.002</td>
<td>(0.0001)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(0.001)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Molybdenium</td>
<td>mg/L</td>
<td>None</td>
<td>Not analyzed</td>
<td>(0.030)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Nitrate (as N)</td>
<td>mg/L</td>
<td>10</td>
<td>6.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Nitrite (as N)</td>
<td>mg/L</td>
<td>1</td>
<td>(0.01)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(0.01)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Selenium</td>
<td>mg/L</td>
<td>0.05</td>
<td>(0.001)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(0.001)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Silver (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>0.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(0.001)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(0.001)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sulfate (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>250&lt;sup&gt;f&lt;/sup&gt;</td>
<td>113</td>
<td>160</td>
</tr>
<tr>
<td>Vanadium</td>
<td>mg/L</td>
<td>None</td>
<td>Not analyzed</td>
<td>(0.01)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Zinc (secondary)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>mg/L</td>
<td>5&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.0115</td>
<td>0.0093&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Organics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organochlorine and organonitrogen compounds</td>
<td></td>
<td>Varies</td>
<td>(varies)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(varies)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Volatile organic compounds</td>
<td></td>
<td>Varies</td>
<td>(varies)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(varies)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Semi-volatile organic compounds</td>
<td></td>
<td>Varies</td>
<td>(varies)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(varies)&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
**Table 2-2. Water quality of springs in the Furnace Creek area and of wells in the Amargosa Farms area (continued).**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Units</th>
<th>Drinking water standard</th>
<th>Select springs of the Furnace Creek area&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Select wells of the Amargosa Farms area&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Navel Spring&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Texas Spring&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total number of observations</td>
<td></td>
<td></td>
<td>2 to 3</td>
<td>1 to 4</td>
</tr>
<tr>
<td>Radionuclides</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alpha particles</td>
<td>pCi/L</td>
<td>15</td>
<td>2.3</td>
<td>3.15</td>
</tr>
<tr>
<td>Radium 226 and Radium 228</td>
<td>pCi/L</td>
<td>5</td>
<td>0.37</td>
<td>0.47</td>
</tr>
<tr>
<td>Uranium</td>
<td>ug/L</td>
<td>30</td>
<td>3.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Gross beta&lt;sup&gt;i&lt;/sup&gt;</td>
<td>pCi/L</td>
<td>None&lt;sup&gt;i&lt;/sup&gt;</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Radon-222</td>
<td>pCi/L</td>
<td>None&lt;sup&gt;i&lt;/sup&gt;</td>
<td>37</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Note: Shaded areas designate sample results that exceed the applicable drinking water standard.

- Source: DIRS 186228-NPS 1994, pp. 113 to 116, 127 to 130
- Source: DIRS 186230-USGS 2009, all
- Source: DIRS 186229-USGS 2009, all
- Source: DIRS 104828-Covay 1997, all.
- This constituent was not detected at the detection limit shown in parentheses. As applicable, the Baseline Water Quality Data Inventory and Analysis Death Valley National Monument (DIRS 186228-NPS 1994, all) reported a value in these cases, but also reported that the average value was computed with 50 percent or more of the total observations that were half the detection limit (that is, half of the observations were reported as not detected, so the "half the detection limit" convention was employed). If there were only two observations in such cases and the minimum and maximum values were the same, then both observations were reported as not detected.
- This average value was computed with 50 percent or more of the total observations that were half the detection limit. Use of half of the detection limit is a common convention when a value is reported as not being detected.
- This constituent and the applicable drinking water standard are not from the primary drinking water standards (that is not from 40 CFR Part 141); rather, they are secondary standards from 40 CFR Part 143, which were set to ensure the aesthetic quality of the drinking water. The secondary standards are not federally enforceable.
- Values shown for copper and lead are action levels that, when exceeded, require the water distribution system to take addition steps to control the corrosiveness of their water (that is, copper and lead are primary concerns with respect to those elements being leached from the distribution system materials).
- Primary drinking water standards include a standard for beta particles and photon emitters, albeit in terms of dose per year (specifically, 4 millirem per year) from average exposure rates. In order to calculate the dose, speciation of the beta particles is required and the analytical results here are only in terms of gross beta values.

mg/L = milligrams per liter.
NDOT = Nevada Department of Transportation.
pCi/L = picocuries per liter.
ug/L = micrograms per liter.
The Highway 95 Fault runs east-to-west in the same general area where the flow system transitions from the Fortymile Canyon section to the Amargosa River section. Subsurface investigations performed by Nye County in this area have led the County to conclude that the Highway 95 Fault is the southern boundary of the volcanic aquifer in the flow path from Yucca Mountain (DIRS 182194-NWRPO 2005, p. 20). Drilling results show volcanic aquifers on the north side of the fault lining up with less-permeable Tertiary sedimentary rocks on the south side. The Nye County evaluation suggests that the contact with the less-permeable rocks forces the southward-flowing groundwater up into the overlying alluvial aquifer system.

Nye County installed another exploratory well (well NC-EWDP-2DB) to the lower carbonate aquifer in the same area of the boundary between the Fortymile Canyon and Amargosa River sections, just south of the Highway 95 Fault and about 19 kilometers (12 miles) south of the repository site. This well also shows an upward gradient from the lower carbonate aquifer to the overlying alluvial aquifers. In this case, water in the deep well rose 7.2 meters (24 feet) higher than the surrounding water table (DIRS 169734-BSC 2004, p. T8-11). At this location, the Paleozoic rock of the lower carbonate aquifer is at a depth of about 820 to 910 meters (2,700 to 3,000 feet) below the ground surface (DIRS 156115-Nye County Nuclear Waste Repository Office 2001, pp. 31-32). (The range in depth below ground surface is the result of different interpretations of the lithology in the well and the depth at which the Paleozoic rock was first encountered.) Since the water table is about 80 meters (260 feet) below the surface in this area, the top of the lower carbonate aquifer is about 740 to 830 meters (2,400 to 2,700 feet) below the top of the water table.

**Discharges or Losses**

There are no identified natural discharges of groundwater (springs or evapotranspiration sites) within the Fortymile Canyon section of the flow system (Table 2-1). Pumping occurs in the section, but the quantity removed is relatively minor. Water supply wells jointly used by the Nevada Test Site and the Yucca Mountain Project are located near Yucca Mountain in the portion of Jackass Flats that is adjacent to Fortymile Wash. As described in the Yucca Mountain FEIS (DIRS 155970-DOE 2002, p. 3-66), water withdrawals from 1992 through 1997 were as high as 400 acre-feet (490,000 cubic meters) per year in this section. As described in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-50), water use in this area has decreased since that time. By the years 2000 and 2001, the quantity used had dropped to about 140 acre-feet (170,000 cubic meters) per year, and from 2002 through 2004, withdrawals dropped further, ranging from 46 to 67 acre-feet (57,000 to 83,000 cubic meters) per year. The latest update to the groundwater withdrawal rates developed for the regional flow system (DIRS 185968-Moreo and Justet 2008, all) estimates the total groundwater withdrawal in 2003 from both Jackass Flats and the Buckboard Mesa area to the north to be 93 acre-feet (114,000 cubic meters) (Table 2-1).

**2.1.1.1.2 Amargosa River Section**

**Recharge and Movement**

Recharge to the Amargosa River section is primarily by throughflow from adjoining sections. The alluvial aquifer receives flow from the Oasis Valley, Crater Flat, and Fortymile Canyon sections to the north and from the Ash Meadows area (labeled as the Specter Range section in Figure 2-2) to the east. The underlying lower carbonate aquifer also receives throughflow from the Fortymile Canyon section and from the Ash Meadows area.
Groundwater (both in the alluvial aquifer and in the underlying carbonate aquifer) from the Fortymile Canyon section enters the central part of the Amargosa River section and flows in a southward direction. In the northwestern part of the section (and northwest of the flow path from Yucca Mountain), the USGS described groundwater movement in the alluvial aquifer as being dominantly lateral and downward toward the regional, lower carbonate aquifer flow paths. In the south-central part of the section, near the Nevada-California border, flow characteristics change and become dominated by upward flow from the carbonate rocks (DIRS 173179-Belcher 2004, p. 155).

Since the Death Valley regional groundwater flow system report (DIRS 173179-Belcher 2004, all) was completed, Inyo County installed an additional well to the lower carbonate aquifer. The County installed this deep well on the California portion of the Amargosa River section, almost directly west of Ash Meadows, and it also has an upward hydraulic gradient from the lower carbonate aquifer to the overlying alluvial aquifer. The well is about 50 kilometers (31 miles) south of the deep well at Yucca Mountain and about 31 kilometers (19 miles) south of the deep well Nye County installed. Water in the Inyo County well rose to an elevation 3.3 meters (almost 11 feet) higher than in an adjacent well [only 6 meters (20 feet) away] installed in the overlying alluvial aquifer (DIRS 185423-ICYMRAO n.d., pp. 4 to 8). Assuming that the bottom of the cased portion of the well represents about the top of the lower carbonate aquifer, the depth to the lower carbonate aquifer in this area is about 750 meters (2,500 feet) below the ground surface (DIRS 185423-ICYMRAO n.d., p. 8). The water table in this area is at about 32 meters (105 feet) below the ground surface, so the top of the lower carbonate aquifer is about 720 meters (2,400 feet) below the top of the water table.

The hydrogeology of the southern portion of the Amargosa River section is particularly complex. On the east side of the section, the lower carbonate aquifer is close to the surface and feeds springs in Ash Meadows. On the west side, the carbonate rocks are lifted and exposed in the southern end of the Funeral Mountains. Moving to the south, the basin-fill deposits narrow (laterally) and become thinner as they encounter hills and mountains. In addition to the thinned basin-fill deposits in this area, groundwater flow to the south is hindered, or at least deflected, by the low-permeability quartzites of the Resting Spring Range (DIRS 173179-Belcher 2004, p. 155).

The Ash Meadows area is not included in Table 2-1 because it is not part of the flow path from Yucca Mountain, but groundwater movement in Ash Meadows is significant to the Amargosa River section. As noted in Section 2.1, the estimated amount of water discharged and lost to evapotranspiration at Ash Meadows is second only to the amount lost from the floor of Death Valley within the entire regional flow system. Estimates put groundwater losses from the Ash Meadows area at over 18,000 acre-feet (22.2 million cubic meters) per year (DIRS 173179-Belcher 2004, p. 155). Most of the spring discharge (not lost to evapotranspiration) recharges the alluvial aquifer of the Amargosa River section; however, much of this is believed to discharge as evapotranspiration from the alluvium along the Amargosa River bed, Carson Slough, and Alkali Flat (DIRS 173179-Belcher 2004, p. 152).

The largest natural pathway by which groundwater throughflow leaves the Amargosa River section is to the southwest through fractures in the carbonate rocks at the southeastern end of the Funeral Mountains. Throughflow leaving by this route moves into the Funeral Mountains section of the Alkali Flat–Furnace Creek basin, primarily toward the springs in the Furnace Creek area of Death Valley or beyond to the floor of Death Valley. As described in the Repository SEIS (DIRS 180751-DOE 2008, pp. 3-34 and 3-35), the evaluation of naturally occurring chemical and isotopic constituents in the water of the Furnace Creek springs link those discharges to the lower carbonate aquifer and, further, have shown them to be
very similar to the water in springs in Ash Meadows. This suggests that groundwater in the lower carbonate aquifer that feeds Ash Meadows is the primary source of the spring discharge in the Furnace Creek area almost directly to the west. However, these same studies suggest there are other contributors to the Death Valley spring discharges, including the volcanic aquifers to the north of Amargosa Desert that contribute to the alluvial aquifer. The evidence indicates the carbonate rocks beneath the Funeral Mountains provide conduits for flow from both the alluvial and lower carbonate aquifers beneath the Amargosa Desert toward the springs in the Furnace Creek area and beyond to the floor of Death Valley.

In summary, groundwater can reach the southern area of the Amargosa River section from several pathways. In the lower carbonate aquifer, groundwater flows in from the north, as well as from the east by way of throughflow from beneath Ash Meadows. In the overlying alluvial aquifer, groundwater can move in as throughflow from the north, as recharge from spring or near surface flows at Ash Meadows, and as upward flow from the lower carbonate aquifer. Once groundwater reaches the southern area of the Amargosa River section, it can leave by one of three identified routes. From the largest to smallest, based on the estimated volume of water involved, these exit routes are as follows: (1) as throughflow to the west via the fractured carbonate rocks beneath the southern Funeral Mountains and into the Funeral Mountains section of the Alkali Flat – Furnace Creek basin; (2) as evapotranspiration, primarily in the area of Alkali Flat and including losses along the Amargosa River and Carson Slough in the same general area; and (3) as throughflow to the south, following the general course of the Amargosa River and through a thin layer of alluvium near Eagle Mountain and into the southern Death Valley subregion (DIRS 173179-Belcher 2004, p. 154). The USGS regional flow model (DIRS 173179-Belcher 2004, all) does not characterize the quantity of flow that might move into the southern Death Valley subregion, other than describing it as minor. The amount of groundwater and quantity of contaminants that could bypass Alkali Flat, while characterized as minor, is not critical for purposes of this Analysis of Postclosure Groundwater Impacts. This is because Chapter 3 of this analysis evaluates discharge areas closer to the repository and assumes discharge of the entire contaminant plume at those areas. Since the types of discharges, water usage, and associated exposure pathways in the southern Death Valley subregion would reasonably be expected to be similar to those Chapter 3 evaluates, exposure scenarios would be the same but with a lower quantity of contaminants. As a result, if some amount of contaminants were to bypass Alkali Flat, there would be a decrease of impacts from those that Chapter 3 presents for the floor of Death Valley and the springs of the Furnace Creek area.

**Discharges or Losses**

Natural discharges within the Amargosa River section are characterized as the evapotranspiration resulting from groundwater seeps and near surface water in the Franklin Well area of the Amargosa River bed and the evapotranspiration from Alkali Flat. The Franklin Well area is an 8-kilometer (5-mile) stretch of the Amargosa River bed in California that runs on the west side of California State Highway 127 (that joins Nevada State Highway 373) near the south end of the Funeral Mountains (DIRS 165609-Lacznia et al. 2001, pp. 14 and 20). It is estimated that 350 acre-feet (432,000 cubic meters) of groundwater are lost each year from the Franklin Well area of the Amargosa River (DIRS 173179-Belcher 2004, p. 107). Alkali Flat is a large playa area located near the southern boundary of the Amargosa River section. Estimates of evapotranspiration losses from this area include not only standing water or near surface water in the main playa area, but also aboveground flow and groundwater seeps along Carson Slough from where the slough leaves the Ash Meadows area to where it joins the Amargosa River bed at the main playa (DIRS 165609-Lacznia et al. 2001, p. 19). It is estimated that 1,000
There are also significant groundwater losses in the Amargosa River section as a result of pumping. Notable irrigation activities began in the Amargosa Desert in the 1970s and continue in the western Amargosa Desert. Groundwater withdrawals in the Amargosa River section have caused local water level declines. This includes the farmed area of Amargosa Desert in the central portion of the section as well as in the northwest portion of the section as a result of mining operations south of Beatty. In the Yucca Mountain FEIS (DIRS 155970-DOE 2002, p. 3-48) groundwater withdrawals in the Amargosa Desert were reported to average about 14,000 acre-feet (17 million cubic meters) per year from 1995 to 1997. The Repository SEIS (DIRS 180751-DOE 2008, p. 3-37) reported that this yearly withdrawal rate decreased to an average of about 13,000 acre-feet (16 million cubic meters) per year from 2000 to 2004. The USGS regional flow model incorporates groundwater withdrawal rates that are slightly different than those reported in the FEIS and SEIS. For example, the latest update to the groundwater withdrawal rates developed for the regional flow system (DIRS 185968-Moreo and Justet 2008, all) estimates a total groundwater withdrawal from the Amargosa Desert of 17,600 acre-feet (21.7 million cubic meters) in 2003. This is compared with a 2003 groundwater withdrawal of about 13,800 acre-feet (17 million cubic meters) from the reference (DIRS 178692-La Camera et al. 2005, pp. 72 and 73) the Repository SEIS cited. Accurate pumping records are not available for all irrigation activities in the area and the differences in published values are attributed to differences in the factors used to generate estimates for unavailable data.

**DIFFERENCES IN GROUNDWATER PUMPING ESTIMATES**

Groundwater pumping estimates for the Amargosa Desert, as identified in previous DOE environmental impact evaluations, are different from those the USGS used in developing the Death Valley regional groundwater flow system model. The primary groundwater use in the area is irrigation. Both estimates are based on documents published by the USGS, but those cited in the earlier DOE documents used irrigation estimates the State of Nevada generated, whereas the regional flow system model used irrigation estimates the USGS generated. Both estimates are based on reliable data on the amount of land under irrigation, but when pumping data are missing, there are differing opinions on what water application rate (amount per acre) should be used to generate an estimate. The regional groundwater flow system model incorporates the larger values of the two approaches. Total annual groundwater withdrawals, as used in the model, averaged 16,800 acre-feet (20.7 million cubic meters) from 1994 through 2003, with a minimum and maximum of 14,100 and 21,200 acre-feet (17.4 and 26 million cubic meters) (DIRS 185968-Moreo and Justet 2008, p.4).

Groundwater pumping described in the preceding paragraph is limited primarily to the west-central portion of the Amargosa Desert. As described in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-38), a 1976 U.S. Supreme Court decision (DIRS 148102-Cappaert et al. v. United States et al. 1976, all) restricted groundwater withdrawal in the Ash Meadows area to protect the water level in Devils Hole and the endangered Devils Hole pupfish. In November 2008, the Nevada State Engineer took further action to protect the federally reserved water rights at Devils Hole. According to Nevada State Engineer Order 1197, any water rights applications within 25 miles (40 kilometers) of Devils Hole, and change applications that place the point of diversion to within 25 miles of Devils Hole, will be denied (with some exceptions) (DIRS 186145-Taylor 2008, all). This 25-mile radius incorporates the Amargosa Farms area of the Amargosa River section and, as a result, the State Engineer’s order could curtail future pumping.
rates in areas more distant from Devils Hole than Ash Meadows. As a result of these actions and restrictions, current pumping rates at the Amargosa Farms area may not be sustainable in the long term.

On an annual basis, the natural groundwater discharges in and near the Amargosa River section consist of the 1,350 acre-feet (1.66 million cubic meters) lost to evapotranspiration within the section, over 18,000 acre-feet (22.2 million cubic meters) lost to evapotranspiration at Ash Meadows, and the minimum of 2,300 acre-feet (2.8 million cubic meters) of throughflow to the Furnace Creek section (discussed further in Section 2.1.1.1.3 below). Based on these values and, more importantly, on the fact that groundwater levels are declining, it is reasonable to conclude that 17,600 acre-feet (21.7 million cubic meters) of annual groundwater pumping in the Amargosa Desert (primarily in the Amargosa Farms area) plays a significant role in the water budget of the section and of the central Alkali Flat – Furnace Creek basin.

2.1.1.1.3 Funeral Mountains Section

Recharge and Movement
As Figure 2-2 shows, the Funeral Mountains section encompasses the central, lowest portion of Death Valley (that is, Badwater Basin), the Funeral and Black mountains along the northeast boundary of the section, and the eastern slope of the Panamint Range along the southwest boundary. Recharge to the section from precipitation is primarily from these mountainous areas, but surface runoff can reach Badwater Basin via Salt Creek from the north or Amargosa River from the south during large precipitation or runoff events within the drainage systems. Since Badwater Basin is the low spot of the regional sink that is Death Valley, groundwater throughflow can reach the section from basically all directions. This includes groundwater moving in from both the northern and southern Death Valley subregions, but a primary source of groundwater coming into the section is throughflow in the lower carbonate aquifer in the southern part of the Funeral Mountains (DIRS 173179-Belcher 2004, p. 155).

Based on the flow paths described previously for the southern portion of the Amargosa River section, the most likely flow path for groundwater originating from beneath Yucca Mountain to reach the Funeral Mountains section would be through the southern part of the Funeral Mountains. A much less likely route would be a round-about way through the southern Death Valley subregions along the general path of the Amargosa River. Along the primary route, throughflow from beneath the Funeral Mountains would first encounter the springs of the Furnace Creek area of Death Valley. Groundwater not discharged at the springs, or discharged and reinfiltrated, then moves in a southwesterly direction toward the floor of Death Valley. There, groundwater is either transpired by stands of mesquite on the lower part of the Furnace Creek fan or evaporated from the playas on the floor of Death Valley (DIRS 173179-Belcher 2004, p. 154). The lowest, and largest, of these playas is Badwater Basin. Other named playas within the Funeral Mountains section include Middle Basin, which is immediately to the north of Badwater Basin, and Cottonball Basin, which is north of Furnace Creek.

The Death Valley floor is surrounded by alluvial fans and numerous springs fringed with vegetation. Groundwater is generally shallow at the bottoms of the fans sloping from the mountains that ring Death Valley. The source of the water in these fans is often local recharge from the mountains, but as in the case of the Furnace Creek area, the source may also be throughflow from adjacent basins.

Discharges or Losses
Natural groundwater losses in the Funeral Mountains section are in the form of spring discharges and evapotranspiration. The largest spring discharges of the section, as well as for the Alkali Flat – Furnace
Creek basin, are those of the Furnace Creek area and include the Texas, Travertine, and Nevares springs. The combined discharge of these springs is estimated at 2,300 acre-feet (2.8 million cubic meters) per year (Table 2-1), of which more than half is from the Travertine springs (DIRS 173179-Belcher 2004, p. 109). By far the largest groundwater loss in the section, however, is by evapotranspiration. The estimated annual evapotranspiration loss from the portion of the Death Valley floor within the Funeral Mountains section is 23,700 acre-feet (29.2 million cubic meters) (DIRS 173179-Belcher 2004, p. 276) (see Table 2-1 above). This value for the central portion of the Death Valley floor represents 68 percent of the 35,000 acre-feet (43.2 million cubic meters) per year of evapotranspiration losses estimated for the entire Death Valley floor (DIRS 173179-Belcher 2004, p. 107).

Groundwater in the Funeral Mountains section supports federal facilities and those of the Timbisha Shoshone Tribe within Death Valley National Park. Most of this water is obtained from the springs of the Furnace Creek area, but there is also a single production well (DIRS 168008-Moreo et al. 2003, p. 20) near the northwestern boundary of the section, in the Stovepipe Wells Village area of Death Valley. The amount of groundwater withdrawn from this well is minor; the 2003 withdrawal was about 55 acre-feet (68,000 cubic meters) (DIRS 185968-Moreo and Justet 2008, database) (Table 2-1).

Death Valley Springs and the Timbisha Shoshone Tribe
Death Valley is within the traditional homeland of the Timbisha Shoshone Tribe, and some members of that tribe reside on a 314-acre parcel of trust land located on the floor of Death Valley near Furnace Creek. The springs in the Furnace Creek area are of traditional and cultural importance to members of the Tribe, and the purity of water in those springs is important to tribal spiritual beliefs, culture, and heritage (DIRS 186231-NRC 2009, pp. 28 to 30). Representatives of the Timbisha Shoshone Tribe have stated that the DOE should evaluate the impacts of the contamination of the Death Valley springs on Timbisha cultural, historic, religious, and other interests, including the Tribe’s rights to continued traditional tribal religious and cultural activities associated with the springs and on the consumptive water rights granted by the Timbisha Homeland Act of 2000 (16 U.S.C. 410aaa) (DIRS 186231-NRC 2009, p. 5). Section 3.5 of this Analysis of Postclosure Groundwater Impacts evaluates the potential impacts to cultural resources and American Indian concerns in that area.

2.1.2 SOUTHERN DEATH VALLEY SUBREGION
The southern Death Valley subregion (Figure 2-3) is divided into four sections, with no basins. The four sections are: (A) the Pahrump Valley section making up the northeast portion of the subregion, (B) the Shoshone-Tecopa section in the north-central portion of the subregion, (C) the California Valley section in the south-central portion, and (D) the Ibex Hills section making up the southwest portion of the subregion. Recharge from the Spring Mountains at the northeast boundary provides groundwater flow in the subregion. Precipitation in the Nopah and Greenwater ranges within the central area of the subregion and in the Kingston Range on the southeastern boundary contribute recharge to a lesser degree (DIRS 173179-Belcher 2004, p. 155). Groundwater throughflow may also enter the southern boundary of the subregion by way of the basin-fill materials in Silurian Valley and in valleys adjacent to the Owlshhead Mountains. A small amount of throughflow into the subregion may also occur across the boundary with the Alkali Flat – Furnace Creek basin of the central Death Valley subregion. As described in Section 2.1.1.1.2, this area of possible groundwater inflow is through a thin layer of alluvium near Eagle Mountain, south of Alkali Flat.
Figure 2-3. Southern Death Valley subregion of the Death Valley regional groundwater flow system.
As with the rest of the regional flow system, groundwater in the southern Death Valley subregion generally moves toward the low floor area of Death Valley. Most of the subregion’s land area is to the northeast of the Death Valley floor (Figure 2-3), so groundwater in most of the region moves generally in a southwesterly direction. A portion of the subregion’s land area, however, is on the southwest side of the Death Valley floor; in this area, groundwater flows generally toward the north and northeast.

Pahrump Valley is the largest discharge area in the subregion. Before extensive development in the Pahrump Valley, the broad playa area had several springs, and the Manse Springs and Bennetts Springs discharged at the base of the broad alluvial fans at the foot of the Spring Mountains. This area now has by far the largest pumping withdrawals in the subregion and flow has ceased in many of the springs. Other areas of natural discharge are along the Amargosa River in the Shoshone and Tecopa areas and in the Saratoga Springs area of Death Valley. Some groundwater may leave the subregion in the northernmost portion, contributing flow to Ash Meadows, and in the southwestern portion, moving past the Saratoga Springs area toward Badwater Basin of the central Death Valley subregion (DIRS 173179-Belcher 2004, p. 155).

The only potential groundwater flow path from beneath Yucca Mountain to the southern Death Valley subregion is across the boundary with the Alkali Flat – Furnace Creek basin in the area south of Alkali Flat and into the Shoshone-Tecopa section of the southern subregion. From the Shoshone-Tecopa section, the primary groundwater flow path basically follows the bed of the Amargosa River to the south into the California Valley section, then to the west into the Ibex Hills section. Since the potential pathway from Yucca Mountain does not include the Pahrump Valley section, that section is not discussed further. The discussion that follows provides additional detail on the three sections of the southern Death Valley subregion that could be involved in the groundwater flow path from Yucca Mountain.

### 2.1.2.1 Shoshone – Tecopa Section

**Recharge and Movement**

Groundwater flow in the Shoshone – Tecopa section is primarily a result of throughflow from adjacent sections with some contribution from recharge in the Nopah Range on the northeastern boundary of the section. Groundwater in the Pahrump Valley section that is not lost in that section moves either to the north of the Nopah Range and into the Shoshone – Tecopa section, or to the south of the Nopah Range and into the California Valley section. That groundwater entering the Shoshone – Tecopa section at the northern end of Chicago Valley joins with groundwater flowing south from the Alkali Flat area and moves southward following the path of the Amargosa River.

**Discharges or Losses**

Groundwater discharge in the Shoshone – Tecopa section is primarily from springs and evapotranspiration along the flood plain of the Amargosa River between the towns of Shoshone and Tecopa, California. Estimates of the amount of groundwater lost to spring discharges and evapotranspiration in the area are about 2,100 acre-feet (2.6 million cubic meters) per year (Table 2-1). The Chicago Valley playa on the east side of the Shoshone – Tecopa section also has evapotranspiration losses. It is estimated that about 430 acre-feet (530,000 cubic meters) of groundwater are lost each year from the Chicago Valley playa (DIRS 173179-Belcher 2004, p. 107).

Documentation for the regional flow system model also identifies some minor pumping withdrawals from the area. Estimates for the Shoshone – Tecopa and California Valley sections are minor and involve only
27 acre-feet (33,000 cubic meters) from two wells in 2003 (DIRS 185968-Moreo and Justet 2008, database; DIRS 173179-Belcher 2004, p. 111) (Table 2-1).

Groundwater not lost to spring discharges, evapotranspiration, or pumping continues flowing south in the alluvium along the Amargosa River and into the California Valley section. Some of the throughflow may also move to the southwest through faulted and fractured crystalline rocks into the Ibex Hills section (DIRS 173179-Belcher 2004, p. 156).

2.1.2.2 California Valley Section

Recharge and Movement
Sources of groundwater flow in the California Valley section are attributed to throughflow from the Shoshone – Tecopa section to the north and from the Pahrump Valley section to the northeast. Recharge from precipitation also occurs on the Kingston Range on the southeast boundary of the section. Groundwater movement in the section is primarily to the south and southwest into the Ibex Hills section.

Discharges or Losses
A structural uplift south of Tecopa brings groundwater to the surface, feeding a perennial stretch of the Amargosa River. As a result, water leaves the section both as surface flow in the Amargosa River and as throughflow in the alluvium along the river. The annual water loss estimate resulting from spring discharges and evapotranspiration along the Amargosa River in the California Valley section is 6,400 acre-feet (7.89 million cubic meters) (DIRS 173179-Belcher 2004, p. 107) (Table 2-1). The minor amount of pumping that occurs in this section was included in the Shoshone – Tecopa section above.

2.1.2.3 Ibex Hills Section

Recharge and Movement
The Ibex Hills section receives groundwater from several directions. In addition to receiving throughflow from the Shoshone – Tecopa section to the north and the California Valley section to the east, the Ibex Hills section likely receives throughflow from outside the regional flow system. As described in Section 2.1.2, groundwater throughflow can enter the southern boundary of the section by way of the basin-fill materials in Silurian Valley to the southeast and in valleys adjacent to the Owlshead Mountains to the south. Groundwater discharge from the lower carbonate aquifer also feeds the area of Saratoga Springs at the southern tip of the Ibex Hills. Groundwater movement is toward the low central area of the section where the Amargosa River bed runs from the southeast to the northwest.

Discharges or Losses
Groundwater discharge in the Ibex Hills section is primarily in the form of spring discharges in the Saratoga Springs area, from evapotranspiration along the Amargosa River and shallow groundwater (that is, groundwater close enough to the land surface that it is subject to evapotranspiration) along the flood plain of the river. A minor amount of groundwater may also leave the Ibex Hills section as throughflow into the central Death Valley subregion to the north, toward the discharge area of Badwater Basin (DIRS 173179-Belcher 2004, p. 156). The estimate of total annual evapotranspiration losses from the portion of the Death Valley floor within the Ibex Hills section is 3,420 acre-feet (4.2 million cubic meters) (DIRS 173179-Belcher 2004, p. 277) (see Table 2-1 above). This value for the southern portion of the Death Valley floor includes losses from Saratoga Springs and is only a minor portion (about 10 percent) of the
35,000 acre-feet (43.2 million cubic meters) per year of evapotranspiration losses estimated for the entire Death Valley floor (DIRS 173179-Belcher 2004, p. 107).

## 2.2 Evidence of Past Climates and the Associated Groundwater Flow System

### 2.2.1 PALEOCLIMATOLOGY

The Yucca Mountain FEIS briefly described DOE’s study and analysis of the evidence of ancient climates (DIRS 155970-DOE 2002, pp. 3-15 and 3-16) in order to gain insight into potential future climates. This study of ancient climates is termed *paleoclimatology*. DOE’s efforts have looked at time scales in the hundreds of thousands of years. This section briefly describes the natural phenomena that drive long-term climate changes. It then describes results of efforts to characterize past climates in the Yucca Mountain region based on these natural phenomena and on evidence of past climates found in geologic evidence in the region.

#### 2.2.1.1 Forcing Mechanisms

To understand how climate has changed over this geologic time scale, DOE’s evaluations, along with those of other investigators, have looked at the forcing mechanisms that drive climate changes. Two of the primary forcing mechanisms have been characterized as *astronomical changes* and *terrestrial changes*.

Astronomical changes are extraterrestrial changes that affect the *solar radiance* received by the earth and include changes in the solar radiance put out by the sun and those due to changes in the way the earth receives that radiance due to its proximity and tilt in relation to the sun. Changes in solar radiance are attributed to sunspot cycles and increasing and decreasing radiance trends of low magnitude over long periods (DIRS 169734-BSC 2004, pp. 6-4 and 6-5). Earth changes are attributed to slight changes in the shape of its orbit around the sun and to changes in the earth’s axis in relation to the plane of the orbit. These cyclical changes in the amount and manner in which the earth receives solar radiance are small, but based on long-term climate records, they show a relationship with *glacial* and *interglacial* periods.

Terrestrial changes refer to the manner in which the earth’s components, consisting of the atmosphere, the water bodies, the solid earth, and life forms, respond to the changes in solar radiance the earth receives. Among these components, the primary forcing mechanisms for climate change, in simple terms, are the interactions between the atmosphere and the oceans as they attempt to minimize temperature differences caused by unequal solar radiance. These interactions and other terrestrial forcing mechanisms, including unpredictable events such as volcanism and asteroid impacts, represent additional critical elements in characterizing ancient climates (DIRS 169734-BSC 2004, pp. 6-7 to 6-9).

Developing an understanding of the natural mechanisms that drive climate changes coupled with physical evidence of past climates has allowed DOE to develop estimates of the climates that could occur in the future and how those climates could affect the performance of the proposed repository.
2.2.1.2 Characterization of Past Climates

A variety of information sources have contributed to an understanding of the paleoclimate in the Yucca Mountain area. The primary sources consist of stratigraphic successions of plant and animal fossils, and the presence of stable isotopes of oxygen and carbon that can be measured and dated. Paleoclimatology studies routinely incorporate numerous other contributing information sets that are not specifically mentioned here. These sources of information of interest are often referred to as climate proxy data because some climate-related parameter, or parameters, can be interpreted.

Information sources, or natural records, covering long periods of time within the Yucca Mountain region consist primarily of Devils Hole in Ash Meadows, Nevada and Owens Lake and Death Valley in California—all within about 160 kilometers (100 miles) of Yucca Mountain. Other sources of information used in the evaluations include plant macrofossil data collected from packrat middens and wetland and spring deposits, which often provide significant information detail, even if it is only applicable to relatively short periods of time (DIRS 169734-BSC 2004, p. 6-26).

DOE evaluated other climate evidence that shows climate episodes similar in magnitude and timing to the Owens Lake and Death Valley data. These included lake and glacial records in the region and records as far away as Greenland, Antarctica, Siberia, and Europe. These records show that climate varied substantially over time and that the timing of those changes is strikingly similar, which provides added support to the concept that climate responds to global forcing mechanisms (DIRS 169734-BSC 2004, pp. 6-40 to 6-44). One of the other records, mentioned below, is the ice core recovered from the Russian Vostok station in East Antarctica. This was a 1998 joint effort among Russia, the United States, and France and resulted in the deepest ice core ever recovered, reaching a depth of 3,623 meters (2.25 miles). Evaluation of data from the ice core indicated that the ice is slightly older than 400,000 years and represents a record extending through four climate cycles (DIRS 109450-Petit et al. 1999, all).

2.2.1.2.1 Devils Hole

Devils Hole, Nevada, is a large fracture within the lower carbonate aquifer that has existed over the past 600,000 years. Calcite that precipitated on rock surfaces over time has left a stable isotope record of the water in the aquifer. The concentrations of isotopes of hydrogen and oxygen deposited in calcite have been shown to vary depending on temperature. As a result, measurements of the isotopes in the calcite provide a climate change chronology, tracking a progression of glacial and interglacial climates. The Devils Hole isotopic data compare well with similar data, including composite records from global oceans and values in ice from cores taken in Antarctica and Greenland. The Devils Hole data provide a good indication of the timing for global climate changes, but do not provide a clear picture of the magnitude of the changes in air temperature and precipitation that were associated with the climate changes (DIRS 169734-BSC 2004, p. 6-28 and 6-29).

2.2.1.2.2 Owens Lake

Owens Lake is a present-day playa in Inyo County, California, about 160 kilometers (100 miles) west-southwest of Yucca Mountain. Over its long history, Owens Lake has varied between being a flow
through lake; a stagnant, saline lake; and a primarily dry playa bed. The playa contains a thick sequence of lake deposits, which include several plant, animal, and geochemical proxies (that is, they provide evidence for specific conditions) for both paleohydrology and climate, and which have been studied extensively in the form of several drill cores collected from the lake bed. These lake deposits provide a record of snow pack in the Sierra Nevada mountains and a measure of the nature, rate of change, and duration of past glacial and interglacial periods (DIRS 169734-BSC 2004, p. 6-30). The chronology of the sediment layers is derived primarily from a model of the sediment accumulation rate. This chronology was subsequently augmented with a radiometric evaluation of pollen profiles that covered 230,000 years of the lake sediment history (DIRS 169734-BSC 2004, p. 6-30).

The geochemistry of the Owens Lake sediments provides significant information on the water that moved through the system. In simple terms, water moving through the system had low concentrations of chemical constituents during glacial periods when runoff was dominated by melt from an extensive snowpack and was higher in geochemical concentrations during interglacial periods (DIRS 169734-BSC 2004, p. 6-31). Fossil diatoms and ostracodes (tiny crustaceans whose remains are commonly preserved in aquatic environments) in the sediments also reflect the range of water chemistry that was in the drainage feeding Owens Lake. The microfossil record shows a chronological progression of climate-induced changes in the hydrochemistry as well as in plant and animal life. One set of species becomes rare or disappears and another set appears and becomes common. The Owens Lake record is relatively continuous and can be interpreted in terms of the global climate changes that are correlated with orbital parameters (DIRS 169734-BSC 2004, p. 6-37).

### 2.2.1.2.3 Death Valley

Sediments in Death Valley, California, also provide evidence of past climate events. During glacial periods, there was a deep lake present in Death Valley and based on evaluations of sediments there and in nearby areas, the Amargosa River was a primary source for that lake. Since flow in the Amargosa River is not supported by runoff from high mountains like the Sierra Nevada, the very presence of the ancient lake at Death Valley appears to support the likelihood that Fortymile Wash, a primary contributor to the Amargosa River, was a permanent stream requiring a groundwater system to support it (DIRS 169734-BSC 2004, p. 6-37). Silver Lake Playa, to the south of Death Valley, was another Pleistocene lake in the region and provides additional evidence that storm tracks may have been displaced southward (compared with the current climate) during glacial episodes.

Other paleohydrologic and paleoclimatic data from Death Valley have been obtained primarily from a 186-meter (610-foot) core taken from the lowest area (Badwater Basin) of the Death Valley floor. The core consists of sediments and evaporites deposited over the last 200,000 years. The core layers were dated using isotopic dating techniques and evaluated for various geochemical constituents to gain an understanding of the physical and climatic conditions under which they were deposited. The core contains halite crystals with fluid inclusions that can be evaluated for the temperature at which the halite precipitated. Based on the strata dating and the fluid inclusion evaluations, investigators have been able to identify periods of time when maximum summer and winter temperatures were similar and how those temperatures compare with those of the current climate. For example, investigators have been able to conclude that temperatures for the majority of the last 100,000 years were lower than temperatures for the modern climate (DIRS 169734-BSC 2004, p. 6-40), which began about 12,000 years ago (DIRS 169734-BSC 2004, p. T6-30).
2.2.1.2.4 Conclusion

DOE’s evaluation of paleoclimatology focused on the relatively short-term history of climate of the tens and hundreds of millennia because that is the time scale of significance to the performance of the proposed repository at Yucca Mountain. The forcing mechanisms described above are expected to function in the future in the same manner as they functioned during the past. Conditions that existed during extremely different climates (such as global aridity during the Triassic period or tropical humidity during the Cretaceous period) involved very different land and ocean configurations. These types of changes in land, mountain, and ocean configurations have not occurred over the past 500,000 years and are expected to change little over the next 500,000 years (DIRS 169734-BSC 2004, p. 6-26); climate swings or perturbations during the past 500,000-year time frame were suppressed in comparison with what the earth experienced during times even further removed from the present, and the climates typical of the recent past likely are representative of those in the future. There is some evidence of earlier (before 500,000 years ago) climate shifts that suggests the long-term earth-based (terrestrial) climate-forcing functions have remained relatively constant only over the past 500,000 years (DIRS 169734-BSC 2004, pp. 6-57 to 6-60).

The various sets of paleoclimatology data collected from the local Yucca Mountain region have been compared with each other to develop the best possible picture of what climate types affected the area and when. These data have also been compared with records of the southwestern United States beyond the Owens Lake – Death Valley region and with various locations around the world, including Greenland, Antarctica, Siberia, and Europe. The evaluations have shown that climate has changed significantly over time and that major changes around the world were synchronized (DIRS 169734-BSC 2004, p. 6-40). The paleoclimatology studies have identified four basic climate types as occurring within the period represented by the Owens Lake record (DIRS 169734-BSC 2004, p. 6-54). These climate types, or states, are as follows:

- Interglacial – A climate comparable to the present, relatively warm climate.
- Monsoon – A climate characterized by hotter summers with increased summer rainfall relative to today.
- Intermediate – A climate (sometimes referred to as the glacial-transition climate) that has cooler and wetter summers and winters relative to today.
- Glacial – A climate that is substantially cooler and wetter relative to today.

The sequencing of these climate states is cyclical, moving from interglacial to glacial and back again. The transitions are termed the intermediate climate state. Monsoonal activity occurs as relatively short bursts within the longer periods of interglacial or intermediate climates.

Figure 2-4 provides a graphical representation of the different climate states and when they occurred during the past 425,000 years. The climate states are largely based on the Owens Lake climate proxies because of the quality of record and the proximity of Owens Lake to Yucca Mountain. However, information from Devils Hole and the Vostok (Antarctica) ice core, which shows a strong similarity to the Devils Hole data, was used extensively to help set the timing of the climate changes depicted in the figure (DIRS 169734-BSC 2004, p. 6-55).
Figure 2-4. Summary of climate occurrences during the past 425,000 years as derived from Owens Lake climate proxies.
Table 2-3 provides a summary of the information presented in Figure 2-4 in terms of the total duration of each climate state. As can be seen in the figure and the table, the Yucca Mountain region experienced the intermediate climate state for the greatest amount of time at almost 60 percent of the past 425,000 years.

**Table 2-3.** Summary of years and percentage for each climate state.

<table>
<thead>
<tr>
<th>Climate State</th>
<th>Total duration during the past 425,000 years</th>
<th>Percentagea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interglacial</td>
<td>82,000</td>
<td>19</td>
</tr>
<tr>
<td>Monsoon</td>
<td>9,000</td>
<td>2</td>
</tr>
<tr>
<td>Intermediate</td>
<td>248,000</td>
<td>58</td>
</tr>
<tr>
<td>Glacial</td>
<td>86,000</td>
<td>20</td>
</tr>
</tbody>
</table>

Sources: DIRS 169734-BSC 2004, pp. T6-29 and T6-30, and Figure 2-4 of this Analysis of Postclosure Groundwater Impacts.

a. The percentage total does not sum to 100 percent due to rounding of the individual percentage values.

The data linked well with global circulation patterns and orbital parameters, thus demonstrating the cyclic nature, *process*, timing, and potential drivers of past climate. The climate proxy data suggest the following (from DIRS 169734-BSC 2004, p. 6-52):

- Numerous climate states occurred during the last 500,000 years ranging from warm interglacial periods (modern climate) to cool or cold and wet glacial periods. The half-million-year span contained glacial periods of different magnitudes ranging from cold and very wet to cool and dry. The maximum temperature during the glacial states of 20,000 to 22,000 years ago is estimated to have been between 4 and 8 degrees Celsius (7 to 14 degrees Fahrenheit) colder than present, with a mean annual precipitation between 1.8 to 2.4 times that of present. This glacial period is considered to have been cool and dry compared with previous glacial periods.

- Past climate states contained periods of high variability with warmer periods occurring in glacial states and cool episodes occurring in warm climate states.

- The modern climate has less *effective-moisture* compared with other climate states.

- Past climates resulted in infiltration and percolation within Yucca Mountain.

**2.2.2 PALEOHYDROLOGY**

Concurrent with its evaluation of paleoclimates, DOE evaluated paleohydrologic evidence. This evaluation of ancient hydrologic conditions in the region of Yucca Mountain has, like the paleoclimatic data, provided insight for assessing the long-term performance of the proposed repository. The paleoclimatology studies described above identified periods of higher effective-moisture (compared with modern conditions) that dominated the last 425,000 years. Similarly, the paleohydrology studies have shown that the low groundwater levels of today might be typical for only the relatively short, drier interglacial periods and that the water table has been higher in the past and would likely rise during future glacial cycles.

The higher effective-moisture of past climate states resulted in the Death Valley region’s lakes, perennial drainage systems, some large wetlands, and many small seeps and minor wetlands (DIRS 120425-D’Agnese et al. 1999, p. 5). Shallow lakes existed in the Gold Flat, Kawich, and Emigrant basins to the...
north and northeast of the Nevada Test Site. Both the Amargosa River and its major tributary, Fortymile Wash, were likely perennial streams helping supply Lake Manly in Death Valley. Cactus Springs, Corn Creek Springs, and Tule Springs, all on the northeast, Las Vegas side of the Spring Mountains, were supported by both groundwater and surface water systems. The higher amounts of recharge in the Spring Mountains and the Sheep Range likely resulted in spring discharge from the alluvial fans at the foot of the mountains (DIRS 120425-D’Agnese et al. 1999, p. 5). This picture of past hydrologic conditions has been obtained through the evaluation of natural features, isotopic data, and mineralogical data, all of which provide evidence of past groundwater levels.

The paleohydrologic information of interest for this Analysis of Postclosure Groundwater Impacts is the identification of areas along potential groundwater flow paths from Yucca Mountain where past conditions may have resulted in groundwater discharge locations not considered in the Section 2.1 discussion of the current groundwater flow system.

2.2.2.1 Ancient Groundwater Discharge Locations

Evidence of ancient, or fossil, spring discharges can take several forms in the southern Great Basin. In areas where water from the lower carbonate aquifer fed the springs, fossil spring deposits are in the form of calcite that forms tufa mounds, travertine terraces, and stratiform deposits. These are all calcium carbonate deposits typical of the Ash Meadows basin and eastern Death Valley, where current discharges are from the lower carbonate aquifer. Deposits in Crater Flat and the Amargosa Desert are from discharges of the alluvial aquifer that were derived primarily from volcanic aquifers, and the amount of carbonate materials is less. Based on the evaluation of fossil spring deposits, the water table might have been from 15 to 70 meters (50 to 230 feet) higher during the Pleistocene (the epoch that lasted from about 1.6 million to 10,000 years ago) than at present (DIRS 169734-BSC 2004, p. 8-97). The discussions that follow address the various paleodischarge sites found in the Yucca Mountain region. Figure 2-5 depicts these ancient discharge sites.

2.2.2.1.1 Ash Meadows

At Devils Hole, evaluation of calcite deposits has shown that the water level was more than 5 meters (16 feet) higher than at present between 116,000 and 53,000 years ago, and fluctuated between about 5 and 9 meters (16 to 30 feet) higher than at present during the period between about 44,000 and 20,000 years ago (DIRS 169734-BSC 2004, p. 8-97). Based on the information in Figure 2-4, both of these time periods included extensive periods of the intermediate climate and some periods of the glacial climate. Investigators have found paleodischarge paths lined with calcite deposits in areas up to 14 kilometers (8.7 miles) north and northeast of Devils Hole in the area often referred to as Amargosa Flat (or Peters Playa). Figure 2-5 shows a large shaded area designated as Ash Meadows. Amargosa Flat is the area that extends to the right, or east, at the top (or north) of the shaded area. Intensive searches for these deposits have shown that they occur at scattered, isolated locations on the surface that coincide with known or suspected faults. They have not been found at similar elevations elsewhere within the basin or along its margin. It is believed that the upward hydraulic gradient in the lower carbonate aquifer may have been even greater during the Pleistocene than at present, and that the scattered evidence of paleodischarges in the Amargosa Flats area was due to upflow along the faults (DIRS 169734-BSC 2004, p. 8-98).
Figure 2-5. Paleodischarge areas in the Yucca Mountain region.
2.2.2.1.2 Southern Crater Flat Area

Investigators found deposits from ancient springs on both the north and south side of the unnamed ridge that defines the southern boundary of Crater Flat. This ridge, or band of hills, extends to the southeast from Bare Mountain, almost reaching the hills extending south from Yucca Mountain. On the north side of the ridge, the Crater Flat Deposit occurs at an elevation of about 840 meters (2,760 feet) above present sea level. There are two deposits on the south side of the ridge: The Lathrop Wells Diatomite site occurs at elevations between 790 and 800 meters (2,590 and 2,620 feet) and the Crater Flat Wash deposit occurs at an elevation of about 790 meters.

Evidence of ancient springs at the Crater Flat sites consists of various mineral deposits, casts of insect burrows, and petrified plants. The Lathrop Wells Diatomite site includes a 1- to 2-meter (3- to 7-foot)-thick bed of diatomite (a soft, chalk-like sedimentary rock rich in the skeletons of diatoms) that is not present at the other sites (DIRS 169734-BSC 2004, p. 8-98). Efforts to date the spring deposits indicate they formed beginning about 60,000 years ago and continued until about 15,000 years ago. It is estimated that the water table needed to be 17 to 30 meters (56 to 100 feet) higher than at present to support the southern springs and 10 to 70 meters (30 to 230 feet) higher at the Crater Flat site (DIRS 169734-BSC 2004, p. 8-99). The compositions of the spring deposits indicate that water from the volcanic and alluvial aquifers generated them. Possibly, but less likely, the composition of the deposits also suggest that they could have been formed by the lower carbonate aquifer (DIRS 169734-BSC 2004, p. 8-100). Current groundwater temperatures in the area indicate there may be upward contributions from the lower carbonate aquifer, possibly along faults in the local area. Thus, there could have been similar contributions in the past.

2.2.2.1.3 State Line Deposits

Ancient spring deposits similar to those at the Crater Flat sites occur along the Nevada-California state line, adjacent to the south end of the Funeral Mountains. The general area starts about where the Amargosa River first enters California, and continues to the southeast to the area where Fortymile Wash joins the riverbed. The present water table is shallow along this reach of the river, which is consistent with it being identified in Section 2.1.1.1.2 as an area with notable evapotranspiration losses. Carbonate-capped terrace deposits indicate that ancient spring discharges occurred as much as 6 meters (20 feet) above the river bottom. Dating of the deposits indicate these high elevation discharges occurred for a span of 30,000 to 50,000 years. Other samples indicate deposit ages as old as 100,000 years and as young as about 10,000 years. These findings are consistent with the belief that the Amargosa River was a major contributor to Lake Manly in Death Valley (Section 2.2.1.2) and appear to show an interplay of surface flow and spring discharge (DIRS 173179-Belcher 2004, p. 158) in a large area where flow from Fortymile Wash joined the Amargosa River.

As with the Crater Flat sites, composition of the State Line deposits indicate water from the volcanic and alluvial aquifers generated them. Possibly, but less likely, the lower carbonate aquifer could have formed the spring deposits (DIRS 169734-BSC 2004, p. 8-100).

2.2.2.1.4 Indian Pass

A final location of ancient spring discharge in the vicinity of Yucca Mountain is near the toe of the northeast-facing slope of the Funeral Mountains. This site, designated the Indian Pass deposit, occurs at
an elevation of 780 meters (2,560 feet) above sea level and has deposits similar to those at the Crater Flat sites, including being of the same general age.

2.2.2.1.5 Other Paleodischarge Locations

Evidence of other ancient lakes and discharge locations within the Death Valley regional groundwater flow system, some of which are mentioned in Section 2.2.2 above, is not addressed further. These other locations are too far removed from potential groundwater flow paths from Yucca Mountain to be relevant to the discussion. For example, the shallow lakes described in Section 2.2.2 that existed in the Gold Flat, Kawich, and Emigrant basins to the north and northwest of the Nevada Test Site are well away from flow paths from Yucca Mountain. Were those lakes to reform during a future, wetter climate, they would not be affected by any contaminants migrating in groundwater away from Yucca Mountain. Similarly, there are wetland deposits in Pahrump Valley (DIRS 173179-Belcher 2004, p. 158) that suggest the area could have surface water in future climates, but that area would not receive groundwater flow from beneath Yucca Mountain.

2.2.2.2 Ancient Groundwater Flow Paths

Groundwater conditions in the vicinity of Yucca Mountain have been modeled several times under different climate scenarios. A focus of earlier efforts was to determine the potential effects of different climate scenarios on the height of the water table at Yucca Mountain and whether the proposed repository might be threatened (DIRS 169734-BSC 2004, p. 8-103). This concern was addressed in the Yucca Mountain FEIS (DIRS 155970-DOE 2002, pp. 3-59 and 3-60) and the Repository SEIS (DIRS 180751-DOE 2008, pp. 3-44 and 3-45) and will not be addressed in this document. The USGS used the regional flow system model of the time to address different climate scenarios (DIRS 120425-D’Agnese et al. 1999, all), but in this case, the goal was to assess the potential impacts on the flow system. The simulation of interest to the current discussion was based on climatic conditions of approximately 21,000 years ago and was intended to represent cooler and wetter conditions during the late Pleistocene under a full glacial condition. This section addresses specific findings from that simulation.

The USGS modeled the cooler and wetter climate of 21,000 years ago primarily by changing the distribution and rates of groundwater recharge over the model grid (DIRS 120425-D’Agnese et al. 1999, p. 1). Results from the climate-change simulation were evaluated by several means, one of which was the comparison of simulated discharge areas with paleodischarge sites. The model results indicated there would have been sufficient groundwater to maintain paleolake levels in the northern parts of the regional flow system and for Lake Manly in Death Valley, and that groundwater discharges occurred at most of the paleodischarge sites. A few exceptions occurred along the east side of the flow system. For example, in Indian Springs Valley, there is evidence of paleodischarges and wetlands in a large area extending north from the present community of Indian Springs. The model failed to identify discharges in this area except for springs closest to the Spring Mountains near the present-day Indian Springs and Cactus Springs (DIRS 120425-D’Agnese et al. 1999, p. 22). The paleodischarge areas closest to Yucca Mountain, however, were reasonably well duplicated, and the simulation is considered a valid representation of paleoclimatic and paleohydrologic conditions.

In conclusion, the model simulation resulted in a raised water table with a potentiometric surface shaped very similar to that for present conditions (DIRS 120425-D’Agnese et al. 1999, p. 1). This means the groundwater flow paths under the simulated past climate condition were basically the same as for the
present day. In addition, the potentiometric surface configuration also predicted surface discharges that match well with identified paleodischarge sites, providing additional confidence in the results. The locations of the primary recharge areas (the mountains) and the regional sink (Death Valley) are the same as at present, further supporting a conclusion that flow paths were not significantly different.

For these reasons, DOE reached the following conclusions with respect to which paleodischarge sites would be in the flow path from Yucca Mountain:

- Ash Meadows. Devils Hole, the other springs within Ash Meadows, and the area of Amargosa Flat (or Peters Playa) are all east of the current flow paths from Yucca Mountain. As a result, the identified paleodischarge locations within the general area of Ash Meadows would not be potential discharge locations for groundwater from beneath Yucca Mountain. Similar to current conditions, water from the lower carbonate aquifer rising to or near the surface in this area resulted in a higher potentiometric surface, or head, in this area, which affected flow paths from Yucca Mountain by keeping the primary paths to the west, closer to the Amargosa River.

- Southern Crater Flat Area. As with the fossil spring deposits of the Ash Meadows area, the Crater Flat sites are not within the current flow paths from Yucca Mountain, and it appears they were not in the flow path in past times when groundwater levels were higher. The groundwater flow path from beneath Yucca Mountain is to the southeast, then basically beneath Fortymile Wash and southward. At its closest, Fortymile Wash is approximately 10 kilometers (6 miles) to the east of the Crater Flat sites.

- State Line Deposits. The State Line fossil spring deposits are in the area where Amargosa River and Fortymile Wash join. This area is in the flow path of groundwater from beneath Yucca Mountain. Both the river and the wash were likely perennial streams during the last glacial period. The USGS’s modeling effort characterized the area bracketed by the confluence of the two streams as a potential wetland area (DIRS 120425-D’Agnese et al. 1999, p. 18). The USGS’s simulation also described the southern part of Fortymile Wash as being a gaining stream (DIRS 120425-D’Agnese et al. 1999, p. 22), meaning groundwater contributed to its flow. Based on a figure provided in the USGS’s report that shows the distribution of drains and constant head cells in the past climate simulation (DIRS 120425-D’Agnese et al. 1999, p. 23), it appears that under the simulation, the gaining portion of the stream extended as far as about 20 kilometers (12 miles) upstream (to the north) from where Fortymile Wash joins Amargosa River.

- Indian Pass. The fossil spring deposits at Indian Pass are located directly southwest, across the Amargosa Desert from the Crater Flat sites. Being even further west of Fortymile Wash than the Crater Flat sites, the Indian Pass site is not within the groundwater flow path from Yucca Mountain.

As identified in the preceding statements, it appears that of the fossil springs, or paleodischarge sites, identified in the vicinity of Yucca Mountain, only the State Line site would be within the groundwater flow path from beneath Yucca Mountain. As a result, this discharge area, along with the southern reach of Fortymile Wash, would be locations where groundwater contaminants originating in the proposed repository could surface under a future cooler and wetter climate.
2.3 Numerical Modeling of the Regional Groundwater Flow System

2.3.1 PREVIOUS WORK

Groundwater modeling efforts in the Death Valley region began more than 20 years ago and have resulted in a succession of models with increasingly more realistic representations of the groundwater flow system. DOE has supported the development of these models for use at the Nevada Test Site and Yucca Mountain to address the complex water resource issues in the region. This section describes some of the earlier efforts and how they contributed to the most recent flow model, the Death Valley Regional Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model. The primary source of information for this section is the USGS report of the same title (DIRS 173179-Belcher 2004, all), and the USGS developed many of the models described.

Results from a series of modeling efforts were published from 1982 to 1995. Two models were developed, one in 1982 and one in 1984, to simulate groundwater systems of the Nevada Test Site and Amargosa Desert, respectively. In 1984, another model was constructed to address the Nevada Test Site and vicinity. All of these were two-dimensional models and each had notable shortcomings; common to each was the inability to reproduce adequate simulations of vertical flow components. In 1987, results of a more sophisticated, quasi-three-dimensional model of the Nevada Test Site regional groundwater flow system were published. This 1987 model consisted of two aquifer layers: the uppermost layer represented a shallow aquifer—for example, volcanic rocks or basin-fill deposits—and the lowermost layer represented a deep aquifer composed of carbonate and volcanic rocks. Although this model represented the Nevada Test Site flow system more accurately than the earlier models, analysis of the model indicated that small changes in recharge or discharge rates generally produced substantial changes in the simulated magnitude and direction of groundwater flow (DIRS 173179-Belcher 2004, p. 14).

Results were published from another model in 1995. In this case, the model was a regional-scale numerical model of the carbonate-rock province of the Great Basin. The conceptual model of the groundwater flow system behind this numerical model was one of relatively shallow components where groundwater moved from mountain ranges to basin-fill deposits in adjacent valleys, as well as a deeper component where groundwater moved through the carbonate rocks. This conceptual model of the groundwater flow system is the basis for subsequent numerical models of the Death Valley regional groundwater flow system.

The more recent efforts have consisted of three-dimensional groundwater flow models, which allowed for a better representation of the spatial and process complexities and heterogeneities of the hydrogeologic system. The efforts have incorporated a three-dimensional hydrogeologic framework model into the groundwater flow model. The hydrogeologic framework model is a digital, computer-based description of the geometry and composition of the hydrogeologic units that are internal to the volume encompassed by the groundwater flow model. This framework provides the basis for assigning the hydrologic properties that directly affect groundwater movement in the groundwater flow model. For example, the hydrogeologic framework model (or a specific unit within that model) provides the initial spatial bounds for a permeability parameter assigned to the model and which can later be modified or adjusted in the flow analysis and calibration. Modeling efforts in this group include a 1996 effort by IT Corporation for the Nevada Test Site and centered on the Nevada Test Site, a 1997 effort for the region around Yucca Mountain, and a 2002 effort that merged elements of the other two models (DIRS 173179-Belcher 2004,
The remaining portion of this section briefly describes these three modeling efforts. Also described is a specific application of the 1997 model.

The 1996 modeling effort by IT Corporation for the Nevada Test Site was undertaken to estimate hydrologic and radionuclide attenuation properties of the rocks through which radionuclides related to nuclear weapons testing might migrate (DIRS 173179-Belcher 2004, p. 15). It included a geologic model with a 2,000-meter (4,920-foot) horizontal grid, with 20 vertical layers of varying thickness, and extending from land surface to 7,600 meters (25,000 feet) below sea level. Twenty hydrogeologic units were modeled. This was integrated into a three-dimensional, steady-state flow model. The model domain encompassed 17,700 square kilometers (6,830 square miles) that centered on the Nevada Test Site and extended west to east from Death Valley to the East Pahranagat Range, and north to south from the southern Railroad Valley to the Black Mountains. DOE also used the model for estimating the amount of water moving through the flow system and associated uncertainties, and for supplying boundary conditions for more detailed models of underground testing areas.

The 1997 modeling effort for the Yucca Mountain Project included a geologic model with a 1,500-meter (6,560-foot) horizontal grid, with variable vertical thickness, and extending from land surface to 10,000 meters (32,800 feet) below sea level. Ten hydrogeologic units were modeled. This was integrated into a three-dimension, steady-state flow model. The model domain encompassed 70,000 square kilometers (27,000 square miles) that centered on Yucca Mountain and the Nevada Test Site and extended west to east from Death Valley to the East Pahranagat Range, and north to south from Cactus Flat to the Avawatz Mountains. The three-layer flow model supported analysis of interactions between the relatively shallow, local and subregional flow paths and the deeper, regional flow paths of the lower carbonate aquifer (DIRS 173179-Belcher 2004, p. 15).

The USGS, in cooperation with DOE, subsequently used the 1997 model to assess the potential effects of past and future climates on the regional flow system. This effort involved the simulation of flow system conditions during the full glacial climate of 21,000 years ago, as well as during future conditions under a scenario involving a doubling of atmospheric carbon dioxide (DIRS 120425-D’Agnese et al. 1999, p. 1). Section 2.2.2.2 describes this modeling effort and results.

In 2002, the hydrogeological framework models from the 1996 and 1997 efforts were merged. This resulted in a single, integrated hydrogeologic framework model for use with a steady-state, prepumping flow model. The three-dimensional flow model incorporated a nonlinear least-squares regression technique to estimate aquifer-system parameters. This model was designated the Death Valley regional groundwater flow system prepumping model, and its lateral boundaries were slightly larger than those of the 1997 model. This model provided a reasonable representation of prepumping conditions for the regional flow system and was an improvement over previous models; however, important uncertainties and model errors remained (DIRS 173179-Belcher 2004, p. 17).

The current USGS model of the Death Valley regional groundwater flow system, published in 2004, builds upon these previous efforts.

### 2.3.2 DEATH VALLEY REGIONAL FLOW SYSTEM MODEL (2004)

In 1998, the USGS began a 5-year project to develop an improved groundwater flow model of the Death Valley regional groundwater flow system. This project was in support of both the Nevada Test Site and
Yucca Mountain Project and was largely funded by DOE. However, because of the model’s potential use in dealing with a wide range of regional water resource issues, several other agencies contributed financially to the work, including Nye County in Nevada, Inyo County in California, the National Park Service, the U.S. Fish and Wildlife Service, and the U.S. Air Force (DIRS 173179-Belcher 2004, p. iii). The initial objectives of this effort included development of the steady-state model representing prepumping conditions (see above). The goal of this project was to provide a starting point for the calibration of a transient groundwater flow model (DIRS 173179-Belcher 2004, p. 7). Ultimately, the model was intended to be used for the following (DIRS 173179-Belcher 2004, pp. 7 and 8):

- Providing the boundary conditions for the site-scale models at Yucca Mountain and Corrective Action Units at the Nevada Test Site;
- Evaluating the impacts of natural or human-induced changes in system flux;
- Providing a technical basis for decisions on the quantity of water available for development on the Nevada Test Site;
- Determining the potential effects of increased offsite water use on Nevada Test Site water supplies;
- Providing a framework for determining effective groundwater quality monitoring locations; and
- Facilitating the development of a cooperative, regional Death Valley groundwater management district.

The 2004 Death Valley regional groundwater flow system model was constructed with 16 layers and a horizontal grid with cells 1,500 meters (6,560 feet) on a side. The total model domain has 194 rows and 160 columns and is essentially the same as the 2002 prepumping model described in Section 2.3.1. The hydrogeologic framework model component includes the geometries of 27 hydrogeologic units that include (from youngest to oldest) (DIRS 186227-USGS 2006, p. 2):

- Cenozoic basin-fill and playa deposits (making up local aquifers and confining units depending on the characteristics of the deposits);
- Cenozoic volcanic rocks (making up aquifers and confining units depending on their physical properties);
- Cenozoic and Mesozoic intrusive igneous rocks (making up local confining units);
- Mesozoic sedimentary and volcanic rocks (making up aquifers and confining units depending on their physical properties);
- Paleozoic carbonate rocks (main regional aquifer);
- Paleozoic to Late Proterozoic sedimentary rocks (main regional confining unit); and
- Proterozoic igneous and metamorphic rocks (regional confining unit, generally forming the bottom of the flow system).
Investigators tested and calibrated the Death Valley regional groundwater flow system model by performing and repeating simulations with adjusted input parameters until water-level and spring-flow values simulated by the model matched the corresponding measured values. The input parameters adjusted during this process included values for parameters of the hydrogeologic units, and recharge and discharge amounts and locations. The model was first calibrated for steady-state groundwater levels developed for prepumping conditions (that is, for conditions before groundwater pumping began in the region in 1913). The model was then calibrated for transient conditions using values for water level, spring flows, evapotranspiration, and pumping as they changed over time from 1913 to 1998 (DIRS 186227-USGS 2006, p. 3).

Results from the model simulations indicated that modeled groundwater flow matched well with inferred groundwater flow patterns throughout the model domain. Simulated groundwater levels generally matched measured water levels except in areas where the water levels change rapidly over a short distance. Areas with this steep hydraulic gradient condition include Indian Springs, western Yucca Flat, and the southern part of the Bullfrog Hills. Water level declines from the transient simulations generally matched those declines observed in Pahrump Valley, Amargosa Desert, and Penoyer Valley. The model also adequately simulated observed spring flow declines in Pahrump Valley during the last century. Finally, the hydrologic parameters of the hydrogeologic units that define the ability of the unit to transmit and store water, and that were adjusted during the calibration process, ended at values within the range of values measured in the field (DIRS 186227-USGS 2006, p. 5).

Section 2.4 of this Analysis of Postclosure Groundwater Impacts provides an overview of the extensive modeling done to evaluate the potential impacts of the proposed repository. The discussion focuses on the movement of water through the unsaturated zone at Yucca Mountain (including through the horizon of the proposed repository), into the saturated zone beneath the repository location, and away from Yucca Mountain in the hydraulically downgradient direction. DOE used site-scale models to simulate water movement in the unsaturated and saturated zones at Yucca Mountain and downgradient past the location of the accessible environment, as defined by regulation (Section 2.4.3.1). Because these site-scale models were developed to simulate a much smaller area than the regional models, they could be developed at much finer detail. Evaluations for this Analysis of Postclosure Groundwater Impacts required that output from the site-scale saturated zone flow model be input to the regional model to evaluate potential impacts from the repository to locations beyond the accessible environment. This involved using the site-scale saturated zone model to track a group of simulated particles from beneath the repository to the boundary of the accessible environment. The distribution of particles from this site-scale model simulation was then input to the regional model, and the particle tracking function was again used to develop simulated flowpaths beyond the accessible environment boundary. The site-scale and regional models can support this action, but transition to the coarser level of detail inherent in the regional model has certain limitations.

DOE has high confidence in the site-scale saturated zone flow model for use in evaluating potential repository impacts. The model includes a horizontal grid with cells 250 meters (820 feet) on a side and 67 layers of varying size or depth in the vertical direction. For comparison, the most recent regional model has a 1,500-meter (4,920-foot) grid size and 16 layers (DIRS 186186-SNL 2009, p. 34). One can visualize the effect of the differences in these model construction parameters in terms of the hydrogeologic framework models. The site-scale and regional models can have the same physical information describing the positions of applicable hydrogeologic units. However, in the regional model, the hydraulic conductivity for an entire cell (defined by one grid in the horizontal plane and one model
layer) is represented by a single geometric mean value calculated from whatever hydrogeologic units are within that cell. Therefore, depending on what units are present, some detail can be lost through the averaging process. In the horizontal plane, the 250-meter grid of the site-scale model offers a resolution that is 36 times finer than the regional model (DIRS 185814-DOE 2008, p. 2.3.9-22).

In the evaluations Chapter 3 describes, the regional model was sometimes used in simulations similar to those for which the site-scale model was used. Variation in model results are recognized and expected; these differences are attributed primarily to the coarse scale of the regional model in comparison with the site-scale, but can also be attributed to the overall purposes for which both models were originally constructed. The regional model was constructed to support simulations from which regional conclusions might be drawn. In some cases, evaluations described in Chapter 3 are based on efforts to use the regional model to define characteristics of discrete flow paths within a small portion of the region. These efforts are within the general capabilities of the model, but the results need to be taken in context of the model’s intended use, the relative coarseness of the model structure, and uncertainties inherent to the modeling process.

2.4 Modeling of Yucca Mountain Infiltration, Groundwater Movement, and Impacts as Described in the Repository SEIS

This section discusses the basis for the groundwater modeling presented in Chapter 3. The discussion is primarily in terms of the modeling associated with the Repository SEIS but also includes how that effort fits with the regional model the USGS developed. Chapter 3 discusses the specific ways in which the current evaluation used the existing models.

The Repository SEIS described results from the Total System Performance Assessment Model/Analysis for the License Application (DIRS 183478-SNL 2008, all), or TSPA-LA, which was used to assess long-term repository performance in terms of a characterization of radiological dose to humans over time. The configuration of the TSPA-LA model provided a framework for the incorporation of information from various process models and abstraction models into an integrated representation of the important features, events, and processes that apply to the repository system, including engineered and natural barriers. Figure 2-6 provides an overview of the principal model components and submodels that were integrated into the TSPA-LA model.

Process models (large, complex computer models) provided information to the TSPA-LA model and included representations of such features as thermal-hydrologic conditions, degradation characteristics of the Engineered Barrier System, and unsaturated and saturated zone flow fields. The process models were based on fundamental laboratory and field data. Abstraction models are generally simpler than the process models, possibly consisting of nothing more than a simple function or table of numbers, but usually representing the results from a much more detailed process model. The TSPA-LA model functioned by handing off data from one subsystem to the next along the primary release path and allowing an assessment of behavior at intermediate points. The integration performed by the TSPA-LA model occurred in a Monte-Carlo simulation-based method to create multiple random combinations of the likely ranges of parameter values for the process models. In this manner, the TSPA-LA model computed
Figure 2.6: TSPA-LA principal model components and submodels.
the probabilistic performance of the entire waste disposal system, and the result reflected an appropriate range of process behaviors or parameter values, or both, of the inherently variable Yucca Mountain Repository system (DIRS 183478-SNL 2008, p. ES-7). Performance was measured in terms of radiological dose to the RMEI located at a distance of approximately 18 kilometers (11 miles) south of the repository, which is the predominant direction of groundwater flow (DIRS 180751-DOE 2008, p. F-4). The TSPA-LA model evaluated the following nine major elements of the Yucca Mountain Repository (DIRS 183478-SNL 2008, pp. ES-8 and FES-9):

- Water flow from the ground surface through the unsaturated tuffs above and below the repository horizon, which would include water that dripped into the waste emplacement drifts;
- Thermal and chemical environments in the Engineered Barrier System, effects of disruptive events on that system, and perturbations to the surrounding natural system due to waste emplacement;
- The degradation of the engineered components that would contain the radioactive wastes;
- The degradation and dissolution of the waste forms and the release of radionuclides from the waste packages;
- The release of radionuclides from the Engineered Barrier System to the unsaturated zone below the repository;
- The migration of these radionuclides through the unsaturated zone below the repository to the saturated zone;
- The migration of these radionuclides from beneath the repository and downgradient through saturated rocks and alluvium to the RMEI;
- Arrival of the radionuclides at the biosphere and their potential uptake by humans at the RMEI location, which could lead to a radiation dose consequence; and
- Disruptive events such as igneous activity, seismicity, and human intrusion (drilling).

The remainder of this section briefly describes how the TSPA-LA modeled the movement of water through the various model components. This section mentions other elements of the repository system that interacted with the modeling of water, but the focus of the discussion is the water as it infiltrates, through the unsaturated zone, reaches the groundwater, and moves away from Yucca Mountain. Appendix F of the Repository SEIS (DIRS 180751-DOE 2008, all) contains additional summary information on other elements of the repository, as well as on the water. DOE’s report on the TSPA-LA (DIRS 183478-SNL 2008, all) provides more detail on the model of the entire repository system.

### 2.4.1 INFILTRATION AT YUCCA MOUNTAIN AND MOVEMENT THROUGH THE UNSATURATED ZONE

This section discusses how the TSPA-LA model treated infiltration and the movement of infiltrating water through the unsaturated zone.
2.4.1.1 Infiltration

The initial water input into the TSPA-LA model is from the site-scale unsaturated zone flow model, which incorporates infiltration at ground surface above the proposed repository location. This infiltration is the precipitation that is not lost to evapotranspiration, runoff, or change in the amount held in the soil or rock, and makes it into the unsaturated zone flow system. Modeling of infiltration for the TSPA-LA model was much different than that used in the TSPA model as described in the Yucca Mountain FEIS. As the Repository SEIS, Appendix F described (DIRS 180751-DOE 2008, pp. F-7 to F-9), the TSPA-LA model used a new infiltration model to increase confidence in the model’s performance. The manner in which climate variation was addressed during the post-10,000-year period was changed significantly to meet requirements proposed by the NRC in changes to Title 10 of the Code of Federal Regulations (CFR) 63.342(c) [Volume 70 of the Federal Register (FR) 53313, September 8, 2005].

The TSPA-LA considered infiltration scenarios for three specific climates for the first 10,000 years after closure: present day (or interglacial), monsoon, and glacial transition (or intermediate). For each of these climates, there was a set of four infiltration rates that represented 10th-, 30th-, 50th-, and 90th-percentile values, which allowed the model to incorporate infiltration rate uncertainty. In modeling the first 10,000 years, the TSPA-LA used the present-day climate for the period from 0 to 600 years; the monsoon climate for the period from 600 to 2,000 years; and the glacial-transition climate for the period from 2,000 to 10,000 years (DIRS 180751-DOE 2008, p. F-8).

The rate of percolation at the repository horizon for the post-10,000-year period was specified by the proposed changes to 10 CFR 63.342(c)(2) (70 FR 53313, September 8, 2005). The proposed rule directed that DOE represent the effects of climate change after 10,000 years by assigning percolation rates at the repository horizon that vary between 13 and 63 millimeters (0.5 and 2.5 inches) per year. DOE implemented this direction by defining the new, temporally averaged climate in the same terms as it used for the three pre-10,000-year climates.

It should be noted that since the Repository SEIS and license application were submitted, the EPA issued a final rule (73 FR 61256, October 15, 2008) governing the post-10,000-year period. The NRC thereafter issued a final rule (74 FR 10811, March 13, 2009) revising 10 CFR Part 63 to implement the EPA’s revision. The final NRC rule revised the deep percolation rate to be used in modeling the post-10,000-year climate slightly upward from that contained in the earlier proposed rule and which was used in the license application. In particular, the NRC’s proposed rule permitted DOE to represent future climate change in the performance assessment by sampling constant-in-time deep percolation rates from a log-uniform distribution with a range of 13 to 64 millimeters (0.5 and 2.5 inches) per year and an average arithmetic mean of 32 millimeters (1.3 inches) per year. By way of comparison, the NRC final rule slightly raised the average arithmetic mean for the deep percolation rate to 37 millimeters (1.5 inches) per year, while broadening the range of the lognormal distribution to between 10 and 100 millimeters (0.39 and 3.9 inches) per year.

The radionuclide fluxes used for this Analysis of Postclosure Groundwater Impacts were the mean results obtained from the outputs of the TSPA-LA, which were developed in accordance with the NRC proposed rule. Because the NRC Final Rule increased the average arithmetic mean of the deep percolation rate distribution from 32 to 37 millimeters (1.3 to 1.5 inches) per year, one would expect the mean radionuclide flux at the location of the RMEI to show only minor, if any, increase. This conclusion is reflected in the NRC’s responses to comments on the proposed amended rule in the Federal Register.
notice of the Final Rule (74 FR 10811, March 13, 2009): (from page 10820) “… dry-to-wet transients in performance assessments would have less influence on the mean of the distribution of projected doses than on any single projected dose used to construct the distribution. …Performance assessment models and analyses continue to improve; however, dry-to-wet conditions appear to have a limited effect on the mean dose within the constraints of current performance assessment approaches.” Therefore, it is unlikely that this slight change in the distribution of deep percolation values would have any significant effect on the mean radionuclide fluxes used in this analysis.

Table 2-4 shows the average infiltration rates the TSPA-LA model used. It is important to note that the rates in the first four rows of the table are the averages over the entire domain of the site-scale unsaturated zone flow model, a larger area than the footprint of the repository. Corresponding infiltration rates over the smaller area of the repository footprint would be slightly larger. As an example, the table also shows infiltration rates for the post-10,000-year period over the repository footprint. These rates are more easily recognized as those proposed by the NRC. The infiltration rate for the post-10,000-year climate is representative of a temporal average that accounts for all four climate conditions expected to occur in the future. As Table 2-4 shows, the post-10,000-year climate is associated with higher infiltration rates than either present-day or glacial-transition climates, which when combined, would account for about 80 percent of the future climate based on paleoclimatology studies described in Section 2.2.1.2 (Table 2-3).

### Table 2-4. Average net infiltration and percolation rates (millimeters per year)* for each of the climates considered in the TSPA-LA.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Percentile</th>
<th>10th</th>
<th>30th</th>
<th>50th</th>
<th>90th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration over the unsaturated zone flow and transport model domain*</td>
<td>Present-day (interglacial)</td>
<td>3.03</td>
<td>7.96</td>
<td>12.28</td>
<td>26.78</td>
</tr>
<tr>
<td></td>
<td>Monsoon</td>
<td>6.74</td>
<td>12.89</td>
<td>15.37</td>
<td>73.26</td>
</tr>
<tr>
<td></td>
<td>Glacial-transition (intermediate)</td>
<td>11.03</td>
<td>20.45</td>
<td>25.99</td>
<td>46.68</td>
</tr>
<tr>
<td></td>
<td>Post-10,000-year</td>
<td>16.89</td>
<td>28.99</td>
<td>34.67</td>
<td>48.84</td>
</tr>
<tr>
<td>Infiltration over the repository footprint (for comparison)*</td>
<td>Post-10,000-year</td>
<td>21.29</td>
<td>39.52</td>
<td>51.05</td>
<td>61.03</td>
</tr>
</tbody>
</table>

*To convert millimeters to inches, multiply by 0.03937.


### 2.4.1.2 Unsaturated Zone

The TSPA-LA model incorporated numerous process and abstraction models to represent the events that would, or could take place in the unsaturated zone; that is, the zone at Yucca Mountain lying between the surface and the water table, which would include the repository. The various system elements are interwoven as necessary to depict complete processes and often involve effects from or to water moving through the zone. For example, a model simulates a breach in a drip shield and in the underlying waste package containment, then incorporates water moving down through the unsaturated zone that could dissolve some of the waste material in the repository and carry that material to the saturated zone. DOE developed several models for the area or zone of the mountain where the repository would be located to represent how contaminants could be released. DOE also developed an unsaturated zone flow model to represent the movement of water in this zone. The unsaturated zone transport model was developed to describe the movement of radionuclides through the natural system below the level of the repository (DIRS 180751-DOE 2008, p. F-18).
The site-scale unsaturated zone flow model of the TSPA-LA was designed to represent the rock mass of Yucca Mountain that would be the pathway of water moving down from the surface, past or through the repository, and to the underlying groundwater. Significant observations from study of the unsaturated zone included these facts (DIRS 180751-DOE 2008, p. F-9);

- Water moves in both fractures and the rock matrix (the solid, but porous, portion of the rock), but generally moves faster in fractures;
- In some areas, water movement along faults can also be significant;
- Water can collect in locally saturated zones (perched water); and
- Water can be diverted in lateral directions due to differences in rock properties at rock layer interfaces or the presence of features such as perched water bodies.

The unsaturated zone flow model that was part of the TSPA-LA represented these physical features of the unsaturated zone. A primary objective of the unsaturated zone flow model was to generate values for the percolation flux at the water table, where percolation flux was defined as the total vertical liquid mass flux through both fractures (and faults) and matrix, expressed as millimeters (or inches) per year (DIRS 184614-SNL 2007, p. 6-80). The flow model also generated percolation flux values at different locations or layers of the unsaturated zone; at those locations, the model generated estimates of the amount of water moving through fractures, the matrix, and in faults (DIRS 184614-SNL 2007, p. 6-91 to 6-96). This feature was used to characterize the nature and quantities of water that would reach the footprint of the repository and included the ability to generate frequency distribution plots displaying the average percentage of the repository area subject to a particular percolation rate. The infiltration model described above provided the net infiltration boundary condition to the unsaturated zone model. The unsaturated zone model used temporally constant, but spatially variable, infiltration boundary conditions for each climate state and generated three-dimensional flow fields for each of the four boundary conditions represented by the 10th-, 30th-, 50th-, and 90th-percentile infiltration rates for each climate.

At the proposed repository horizon (or repository level), the unsaturated zone flow model integrated with several other models representing processes that would affect the movement of water and transport of radionuclides in or near the unsaturated zone. Some of these other models are described as follows:

- A thermal hydrology model represented the effects that heat generated by the waste would have on water movement near the emplacement drifts. During an initial period after emplacement of the nuclear materials, water and gas in the heated rock would be driven away from the repository drifts. Over time, the thermal output of the material decreases, the rock returns to its normal temperature, and the water and gas flow back toward the repository (DIRS 180751-DOE 2008, p. F-11).
- A seepage flow model characterized how water would move when it reached drift walls. In many areas, the capillary effect at the drift walls would have a barrier effect and cause water to be diverted around the drift. In other areas, hydrogeologic properties would focus water movement and cause a seep into the drift. As infiltration would increase with changing climates, the number and locations of seeps would tend to increase. DOE based the seepage model on measurements from tests in the Exploratory Studies Facility (DIRS 180751-DOE 2008, p. F-10) and designed the model to include probability distributions for the fraction of waste packages that could encounter seepage and the seep...