Summary of Groundwater Flow Models of the Death Valley Regional Aquifer System and Yucca Mountain Area

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–07–006

Prepared by

J. Winterle
L. Gergen

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

September 2011

ABSTRACT

This knowledge capture report provides a brief summary of numerical groundwater models of the Death Valley Regional Groundwater Flow System (DVRFS) and the Yucca Mountain area. The main focus of the report is on the Death Valley Regional Groundwater Flow Model (DVRGFM), developed by the U.S. Geological Survey in cooperation with the U.S. Department of Energy (DOE) to support the DOE characterization of Yucca Mountain as a proposed repository for high-level radioactive waste. The DVRGFM is important in that it describes the regional hydrogeologic setting in which the Yucca Mountain area resides. The second focus of this report is to provide a short bibliography of smaller scale groundwater models and modeling studies in and near the Yucca Mountain area. This bibliography is not intended to be exhaustive and judgment was used in deciding which studies are most relevant. The intent is that the included bibliographic summaries would provide a qualified hydrogeologist with a useful starting point for understanding the current state of knowledge about the Yucca Mountain groundwater flow system.

CONTENTS

FIGURES

Figure | Page

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for the U.S. Nuclear Regulatory Commission (USNRC) under Contract No. NRC–02–07–006. The activities reported here were performed on behalf of the USNRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the USNRC.

The authors would like to thank Gordon Wittmeyer for technical review and E. Pearcy for programmatic and editorial reviews. The authors also appreciate L. Selvey for providing word processing support in preparation of this document.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No original data were generated for this report.

ANALYSES AND CODES: No technical analyses or codes are presented or used in this report.

1 INTRODUCTION

This report provides a brief summary of numerical groundwater models of the Death Valley Regional Groundwater Flow System (DVRFS) model since 1995. A previous summary of models within the DVRFS was completed by Wittmeyer and Turner (1995). Since that time, however, a three-dimensional regional model of the entire DVRFS has been developed and has gone through several updates and improvements. Additionally, site characterization in support of the Yucca Mountain Project has spurred the generation of several smaller scale groundwater models within the DVRFS.

The purpose of this knowledge capture report is to consolidate in one place a summary of the groundwater models created since 1995 that are most relevant to Yucca Mountain. The main focus of the report is on the Death Valley Regional Groundwater Flow Model (DVRGFM), developed by the U.S. Geological Survey (USGS) in cooperation with the U.S. Department of Energy (DOE) to support the DOE characterization of Yucca Mountain as a proposed repository for high-level radioactive waste. The DVRGFM is important in that it describes the regional hydrogeologic setting in which the Yucca Mountain area resides. Accordingly section 2 of this report provides a summary of the development DVRGFM and how it was used to support the DOE characterization of the Yucca Mountain site.

A second focus of this report is to provide, in Section 3, a short bibliography of smaller scale groundwater models and modeling studies within the DVRFS that provide useful information and context for understanding groundwater flow in and around the Yucca Mountain area. This bibliography is not intended to be exhaustive and judgment was used in deciding which studies are most relevant. The intent is that the included bibliographic summaries will supplement the report by Wittmeyer and Turner (1995) to provide a useful starting point for understanding the Yucca Mountain groundwater flow system.

2 THE DEATH VALLEY REGIONAL GROUNDWATER FLOW MODEL

2.1 Physiography and Geology of the Death Valley Region

The Great Basin, 500,000 km^2 [200,000 mi^2] and part of the Basin and Range physiographic region, is characterized by arid climates and internal drainage of surface water and ground water (Mifflin, 1988). The Death Valley regional flow system lies within the carbonate-rock province of the southern Great Basin. A deep regional aquifer formed of thick sequences of highly permeable Paleozoic carbonate rocks, fosters interbasinal groundwater flow between topographically closed structural basins (DOE, 2008a; Wittmeyer and Turner, 1995). As illustrated schematically in Figure 2-1, regional groundwater flow in the DVRFS through the Paleozoic carbonate rock sequence is affected by complex geologic structures from regional faulting and fracturing that can enhance or impede flow (DOE, 2008a). Permeable Cenozoic basin fill throughout the DVRFS, and fractured Cenozoic volcanic rocks near the Nevada Test Site (NTS) form locally important aquifers that interact with regional flow through the underlying Paleozoic carbonate rocks (Sweetkind, et al., 2004; Winograd and Thordarson, 1975). Primary regional confining units include Proterozoic to Lower Cambrian metamorphic and siliciclastic rocks and Paleozoic siliciclastic rocks. Local confining units are composed of fine-grained Cenozoic basin fill, and zeolitically altered and nonwelded Cenozoic tuffs (Winograd and Thordarson, 1975).

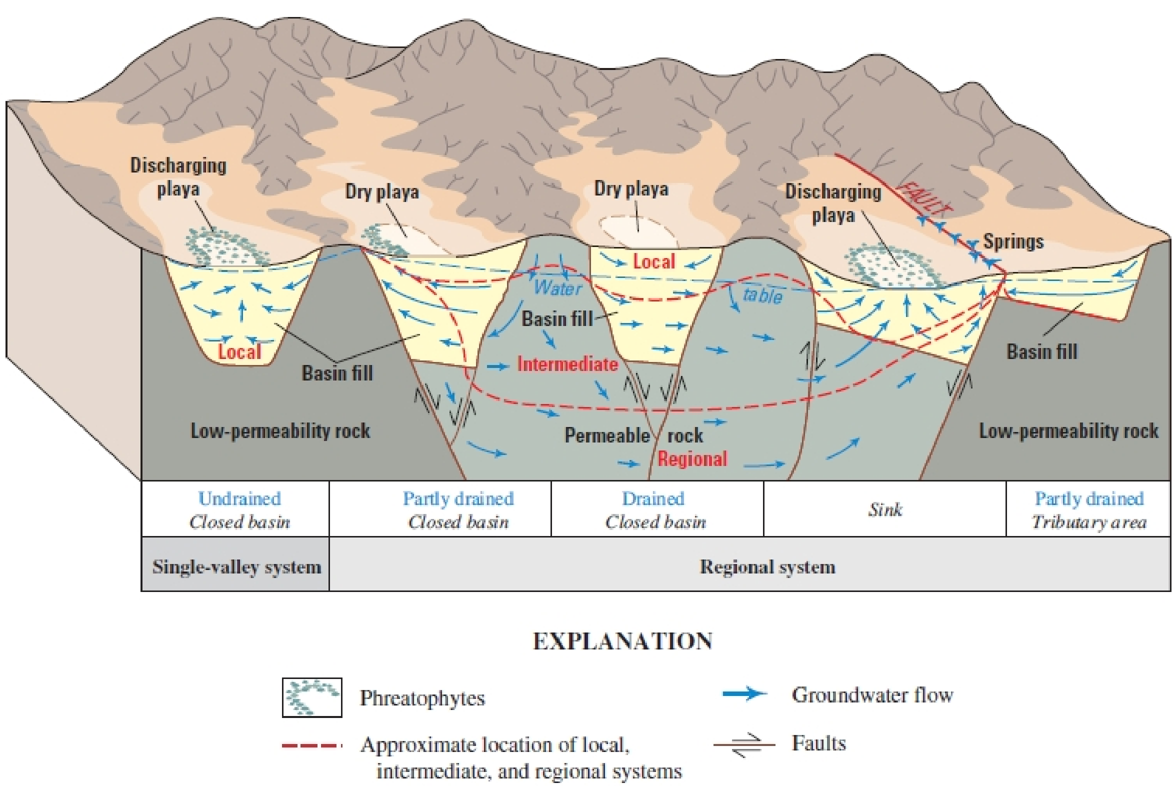

Figure 2-1. Schematic Block Diagram of Death Valley and Other Basins Illustrating the Structural Relations Between Mountain Blocks, Valleys, and Groundwater Flow (Faunt, et al., 2004a, Figure D–1)

2.2 Model History

This section provides a summary of the evolution of the DVRGFM and how the different model versions and model analyses may have been used in the Yucca Mountain site characterization effort.

D’Agnese, et al. (1997)

USGS developed the DVRGFM in cooperation with DOE to support the DOE evaluation of Yucca Mountain as a proposed repository for high-level radioactive waste (D’Agnese, et al., 1997). The model covers much of the approximately 100,000 km^2 [39,000 mi^2] area of the DVRFS in Nevada and California. The initial three-dimensional steady-state model was developed by D'Agnese, et al. (1997) using a computational grid with three vertical layers and a lateral grid composed of 1,500-m [4,900 ft] square cells. The model was constructed and calibrated using the numerical flow model MODFLOWP (Hill, 1992) to simulate present-day conditions.

Calibration included adjusting (i) the location and type of flow system boundary conditions, (ii) the extent of recharge areas, and (iii) the arrangement of hydrogeologic framework features. Spring flow and water level data were used as calibration targets. During model calibration, the original single recharge parameter was reassigned into four zones with percentages of infiltrating average annual precipitation designated. Additionally, although the initial model included only four hydraulic conductivity zones, refinement was necessary to better represent geologic structures and lithology, resulting in assignment of nine hydraulic conductivity zones.

This 1997 version of the model provided a framework for understanding regional flow patterns within the DVRFS. Calculated flow rates from the DVRFS model provided estimated flow rates that were used to aid calibration of the smaller-scale DOE site-scale saturated-zone flow model of the Yucca Mountain region (BSC, 2004a).

D’Agnese, et al. (1999)

The 1997 steady-state model provided a starting point for D’Agnese, et al. (1999) to assess the effects of climate change on the DVRFS. The purpose of this model was to understand how potential future climate conditions might influence groundwater flow rates that, in turn, may affect radionuclide transport from the proposed repository to the accessible environment. Past (full-glacial) and future (global-warming) climate scenarios were evaluated. Simulated results of past climatic conditions 21,000 years before present were compared to observations of paleodischarge sites. Past (full-glacial) climate conditions were wetter and cooler than today, with lakes, perennial streams, and large wetlands common. In general, the present-day model parameters and boundaries (D’Agnese, et al., 1997) were used for modeling the past climate conditions with the following changes:

1. Constant-head cells were used to simulate paleolakes present 21,000 years ago.

2. Constant-head cells along the northern and northeastern edge of the lateral model boundaries were assigned to all 3 layers in the past model, as opposed to only layer 3 in the present-day model. This allowed for potentially larger underflow of groundwater into the model domain.

3. Recharge rates were increased to reflect glacial climate conditions.

4. Recharge distribution was changed because of different precipitation patterns.

5. The drain package was used to convert evapotranspiration areas into wetlands, and to simulate surface runoff in mountain-top areas where potential recharge water exceeds hydraulic conductivity.

6. Pumping from wells was eliminated.

In mountain ranges with low hydraulic-conductivity units, the increased recharge exceeded the hydraulic conductivity of the formation; in those cases, the excess portion of recharge was assumed to become surface runoff, referred to by D'Agnese, et al. (1999) as "rejected recharge." For the wetter past-climate scenario, simulated recharge increased 5.4 times over the model domain and 7 percent of the assigned recharge was rejected. This model produced a similarly shaped but higher regional potentiometric surface, with more pronounced large hydraulic gradients. Groundwater discharge was predicted at most of the observed paleodischarge sites, indicating simulated recharge distributions were reasonable. Water levels were 60–150 m [200–490 feet] higher beneath Yucca Mountain. The proposed repository level is located 200–400 m [655–1,310 ft] above the present day water table and is a minimum of 50 m [165 ft] above the past-climate simulation water table elevation.

Future (global warming) climate conditions represent an anthropogenic "worst-case" scenario with a doubling of atmospheric carbon dioxide due to burning of all estimated fossil-fuel reserves (D'Agnese, et al., 1999). The warming condition had less precipitation than the past-climate (glacial) scenario resulting in generally less recharge input to the model. The present-day model parameters and boundaries (D'Agnese, et al., 1997) were used in the future-climate simulations, except as noted below:

1. Constant-head cells were assigned to all three layers at lateral boundary areas where interbasinal flow was assumed to occur, as opposed to only layer 3 in the present-day model. This allowed for potentially larger underflow of groundwater into the model domain. Note, however, that most of the lateral boundaries were treated as no-flow to represent the predominantly closed-basin characteristics of the DVRFS.

2. Total recharge was greater than for present-day simulations. Recharge rates were increased for higher altitude areas, and less than or equal to present-day for the rest of the model.

3. Recharge distribution was changed because of different precipitation patterns. A much larger portion had zero recharge compared to the past-climate simulation.

4. The drain package was used to convert evapotranspiration areas into wetlands, and to simulate surface runoff in mountain tops where recharge exceeds hydraulic conductivity.

5. Future pumping remained constant at present-day rates.

Under future-climate conditions, simulated recharge increased 1.8 times over parts of the model domain, or remained constant or even decreased in other parts of the domain, relative to present day. In mountain-top areas where recharge exceeded hydraulic conductivity, 1.2 percent of recharge was rejected, representing surface runoff. This increase in recharge resulted in only slight changes in the configuration of the potentiometric surface. Large hydraulic gradients observed in present day were maintained or enhanced in some areas.

Simulated water levels were less than 50 m [165 ft] higher beneath Yucca Mountain. The proposed repository horizon is 200–400 m [655–1,310 ft] above the present-day water table and at least 150 m [490 ft] above the future climate (global warming) scenario water-table elevation.

This 1999 modeling analysis provided the basis for estimating the increase in water flow rates in the Yucca Mountain area under future wetter climatic conditions, the change in upward hydraulic gradients between the underlying regional Paleozoic carbonate aquifer and the overlying volcanic rocks, and simulated the increased recharge under glacial-transition climates (DOE, 2008b).

D'Agnese, et al. (2002)

Following development of the D'Agnese, et al. (1997) model, the DOE [Office of Environmental Restoration and Waste Management, and National Nuclear Security Administration (NNSA)] requested the USGS to develop a steady-state model to determine predevelopment conditions of the DVRFS. The conceptual model and geologic interpretations from the 1997 and 1999 models were incorporated into the 2002 model (D'Agnese, et al., 2002) and the model was updated to use MODFLOW-2000 (Harbaugh, et al., 2000). The 2002 model was designed to (i) provide the foundation and boundary conditions for the site-scale models at Yucca Mountain and the Underground Test Areas on the NTS, (ii) define regional three-dimensional groundwater flow paths, (iii) determine discharge and recharge locations, (iv) estimate magnitude of subsurface flux, and (v) account for the effect of regional geologic structural features on regional flow.

A net infiltration model was developed to update estimates of regional ground-water recharge. All water that infiltrates past the "root zone" was assumed to eventually become groundwater recharge. Precipitation on the higher mountains in the region is the main source of recharge to the regional groundwater flow system (Figure 2-2). Interbasin flow from outside of the DVRFS also contributes to recharge, as well as recycled irrigation and domestic waters, and spring discharge seepage.

Groundwater discharge occurs locally and is mainly through evapotranspiration due to the arid climate in the DVRFS (Figure 2-3). Water stored in shallow unconfined aquifers accessible to vegetation and at the water table is connected to the atmosphere. Most of the water evapotranspiring in these discharge zones originates from spring or seep flow or as diffuse upflow from lower regional confined aquifers.

New techniques available in MODFLOW-2000 allowed for improved calibration with observed hydraulic heads and spring flows. During calibration, four types of conceptual models were analyzed using the regression methods in MODFLOW-2000. These include modifications to (i) the location and type of flow-system boundary conditions, (ii) the delineation of discharge areas, (iii) the definition of recharge areas, and (iv) the configuration of hydrogeologic framework features. For each change, a new set of parameters was estimated employing MODFLOW-2000, and simulated heads and groundwater discharges were compared with observed values. Conceptual model changes with >10 percent improvement in model fit, as demonstrated by a reduction in the sum of squared errors, were incorporated into the final model. Refinements to the hydrogeologic framework interpretation did the most to improve the numerical model fit.

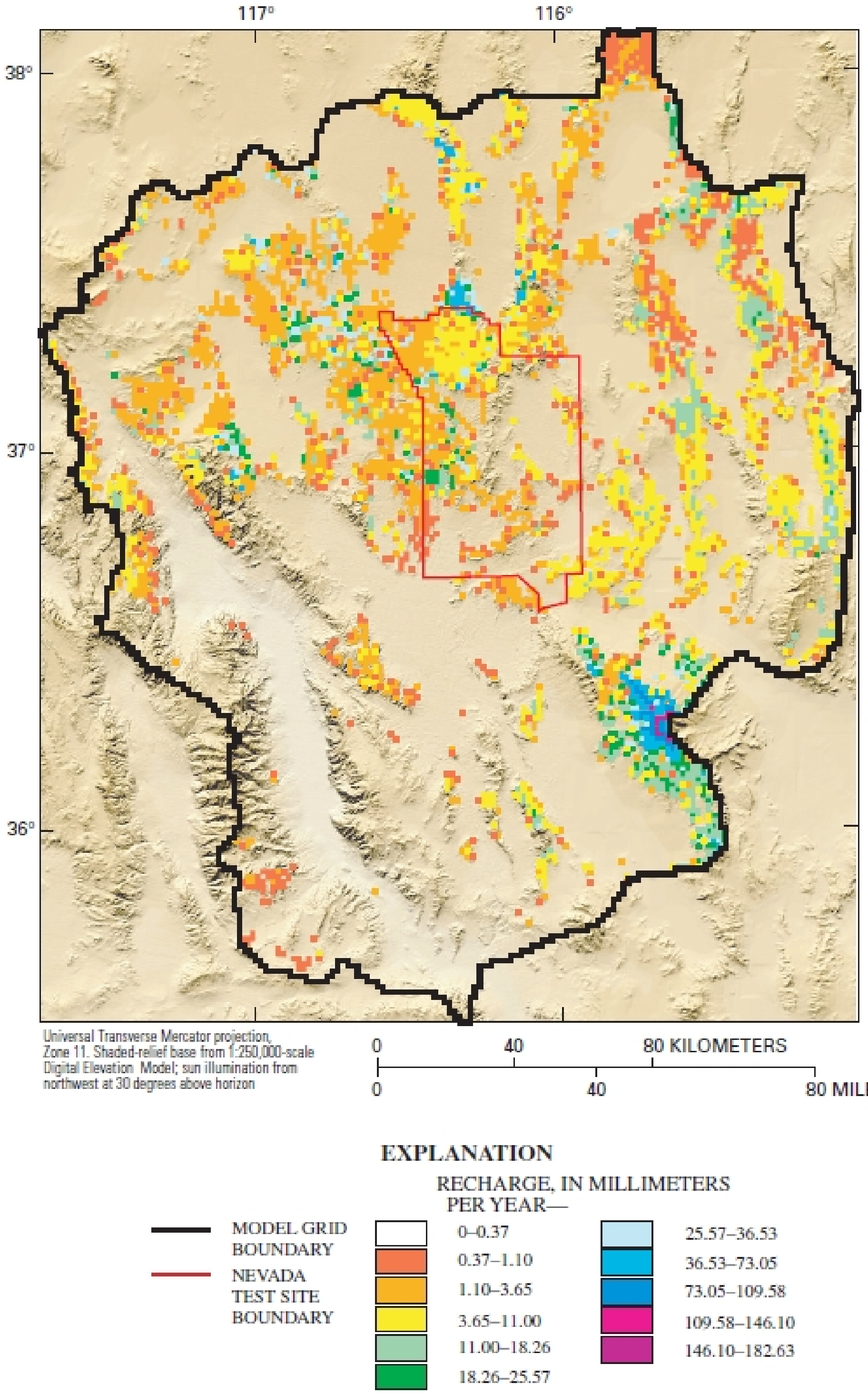

Figure 2-2. Recharge Simulated in the Death Valley Regional Flow System Model (D'Agnese, et al., 2002, Figure 21)

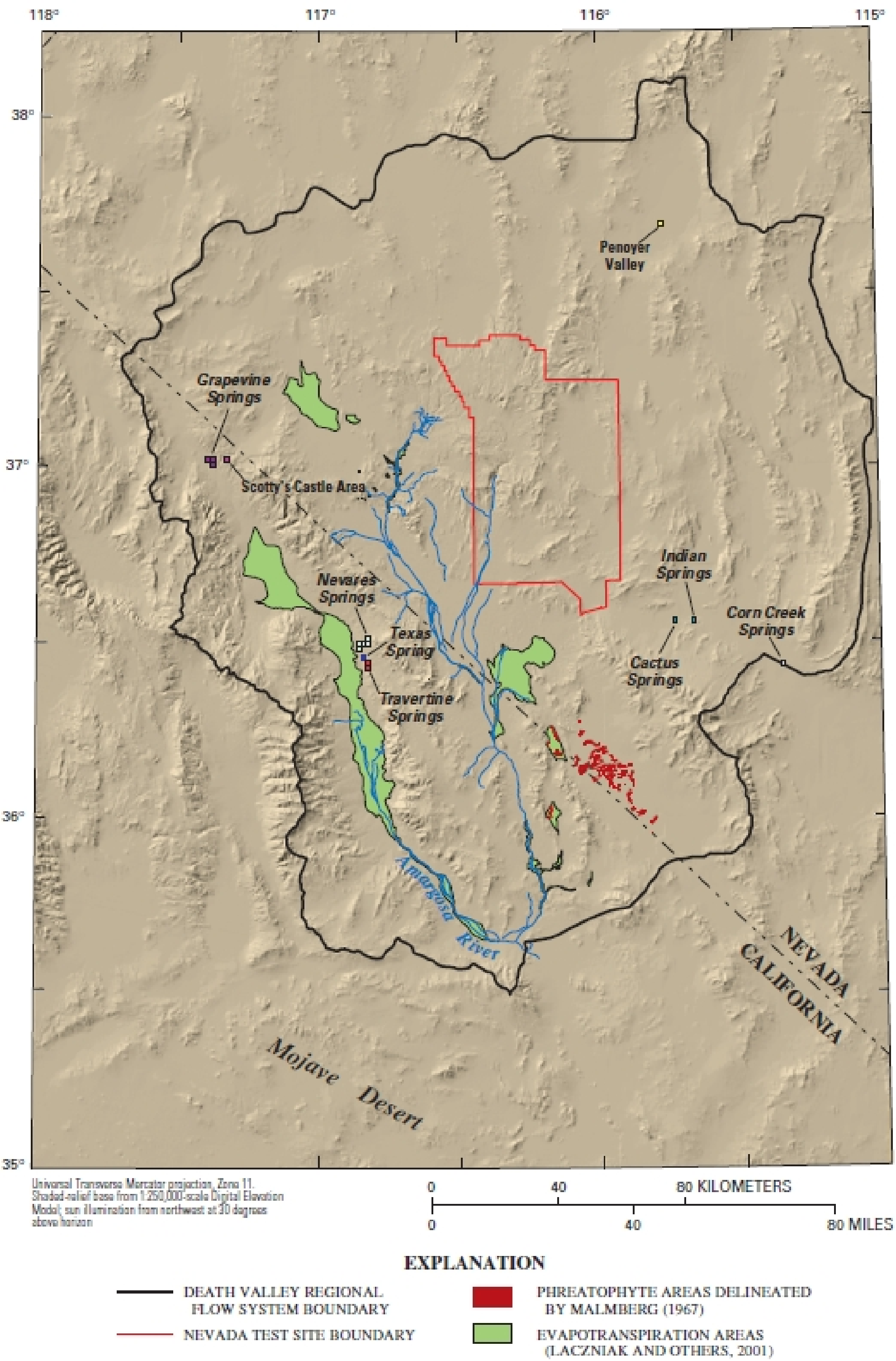

Figure 2-3. Groundwater Discharge Areas in the Death Valley Regional Flow System (D'Agnese, et al., 2002, Figure 13)

The steady-state prepumping DVRFS model was deemed by USGS to be an acceptable representation of the prepumping conditions for the DVRFS and an improvement over previous models (Belcher, et al., 2004). Uncertainties and errors are a consequence of (i) the quality of interpretation and representation of flow-model observations, (ii) geometry and spatial variability of hydrogeologic materials and structures in the hydrogeologic-framework and groundwater flow models, and (iii) the physical framework and the hydrologic conditions in the flow model (D'Agnese, et al., 2002). Belcher, et al. (2004) noted that some uncertainty also arises from treating the flow system as confined in locations where an unconfined water table is predicted.

<u>Belcher (2004)</u>

In 2004, the USGS merged an IT Corporation (1996) model (designated DOE/NV-UGTA) with the 1997 ground-water flow model to produce a transient flow model of the Death Valley regional ground-water flow system (Belcher, 2004) for DOE (Office of Environmental Management, NNSA). The DOE/NV–UGTA flow model was used to evaluate the transport of radionuclides from Nevada Test Site underground nuclear weapons tests. The purpose of Belcher's (2004) model was to assimilate and reevaluate decades of groundwater flow system study and previous groundwater flow models and incorporate new data to develop and calibrate a more complex, transient model simulation. The intended uses of the model were to provide boundary conditions for site-scale models; assess the consequences of changes in system flux; provide a technical basis for decisions on the quantity of water available for development activities; determine source plumes, ambient trend, and point-of-use ground-water quality monitoring locations; and help initiate a regional Death Valley ground-water management district (Belcher, et al., 2004). Belcher (2004) contains several chapters by other authors, which are referred to individually throughout this report.

MODFLOW-2000 (Harbaugh et al., 2000) was again used in this model. Updates included use of a three-dimensional digital hydrogeologic framework model (HFM) developed from digital elevation models, geologic maps, borehole information, geologic and hydrogeologic cross sections, faults and fractures, and other three-dimensional models to represent the geometry of 27 different hydrogeologic units (HGUs) (Sweetkind, et al., 2004). The detail afforded by the HFM and by MODFLOW-2000 improved spatial accuracy for every model parameter. To further enhance accuracy, additional data were collected on the lithostratigraphy and structural effects of the hydrogeologic framework and recharge and discharge estimates. Boundary inflow and outflow estimates also were reevaluated (Belcher, 2004).

The 2004 model was cited in the DOE license application for Yucca Mountain (DOE, 2008b) and provided recharge and discharge boundary conditions (locations where water enters or leaves the domain of the Yucca Mountain site-scale model). These estimates of underflow were used to calibrate the Yucca Mountain site-scale model lateral boundary inflows and outflows to the flows predicted in the regional model. In addition, the site-scale saturated-zone flow model (Sandia National Laboratories, 2007a) uses 23 of the 27 hydrostratigraphic units identified in the DVRGFM hydrogeologic framework model. The 2004 model update, while more complex than the previous version, did not result in significant changes to the input, calibration, or output relating to the previous Yucca Mountain site-scale model (BSC, 2004a).

The model was first calibrated to prepumped steady-state flow conditions. The calibrated steady-state model then provided the initial conditions for the transient-flow model, which was then calibrated to simulate transient-flow conditions that included pumping for the years 1913–1998.

The largest pumping center included in the model is in Pahrump Valley, in the southern Death Valley subregion, with as many as 7,876 wells pumping 2.21 × 10^9 m^3 [7.80 × 10^{10} ft^3] from 1913 through 1998 (Figure 2-4). The central Death Valley subregion has a total of 675 wells pumping 1.06 × 10^9 m^3 [3.74 × 10^{10} ft^3], focused in the Alkali Flat- Furnace Creek groundwater basin, Ash Meadows groundwater basin, and Pahute Mesa-Oasis Valley groundwater basin. The northern Death Valley subregion only has 16 wells pumping 1.11 × 10^6 m^3 [3.92 × 10^7 ft^3] (Faunt, et al., 2004b).

Faunt, et al. (2004b) concluded that the three-dimensional model simulated observed values reasonably well with downward hydraulic gradients in recharge areas and upward hydraulic gradients in discharge areas. Some model limitations recognized by Faunt, et al. (2004b) include (i) inadequacies or inaccuracies in observations used in the model (i.e., clustering causing overemphasis of observations in isolated areas, and difficulty assessing prepumping conditions for steady-state calibration in agricultural areas with pumping wells); (ii) the hydrogeologic interpretation (geometric complexity of hydrogeologic materials and structures simplified in HGUs result in the removal of the effects of small-scale variability); and (iii) the scale represented by observations in the flow model compared to the 1,500-m [4,920-ft] resolution of the flow model grid. Faunt, et al. (2004b) also noted that the net-infiltration model may overestimate recharge somewhat because water passing the root zone is assumed to reach the water table and is not able to be diverted, perched by a lower permeability layer in the unsaturated zone, or evaporated from deep within the unsaturated zone. Other reasons for overestimating recharge include: (i) lateral-flow boundary conditions are poorly understood due to lack of data, (ii) use of the Drain package to simulate discharge attributed to evapotranspiration could be improved by using a more accurate evapotranspiration package, and (iii) seasonal irrigation pumpage could be accounted for by decreasing the length of the year-long stress periods (Faunt, et al., 2004b).

<u>Belcher and Sweetkind (2010)</u>

Belcher and Sweetkind (2010) formalizes the material originally presented in Belcher (2004) with errors and inconsistencies within and between chapters corrected and the clarity and accuracy of a number of the figures improved. Other than these relatively minor changes, it is essentially the same as document as Belcher (2004). Note that DOE cites the Belcher (2004) version of the document in their Yucca Mountain Repository License Application (DOE, 2008a,b).

2.3 Insights on Groundwater Flow Patterns and Directions in the Yucca Mountain Area Gained From Results of the Death Valley Regional Groundwater Flow Model

The DVRFS is a major regional flow system in which groundwater flows between recharge areas in the mountains of central and southern Nevada and discharge areas of wet playas and springs, south and west of the NTS and in Death Valley. The DVRFS model domain is divided into northern, central and southern Death Valley subregions, as shown in Figure 2-5. The central subregion is divided into the Pahute Mesa-Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek groundwater basins, as shown in Figure 2-6. The Alkali Flat-Furnace Creek basin is further divided into the Fortymile Canyon, Amargosa River, Crater Flat, and Funeral Mountains sections. Yucca Mountain is located in the central Death Valley subregion, the Alkali Flat- Furnace Creek basin, and borders the Fortymile Canyon and Crater Flat sections. The boundaries of these subregions, basins, and sections do not define independent

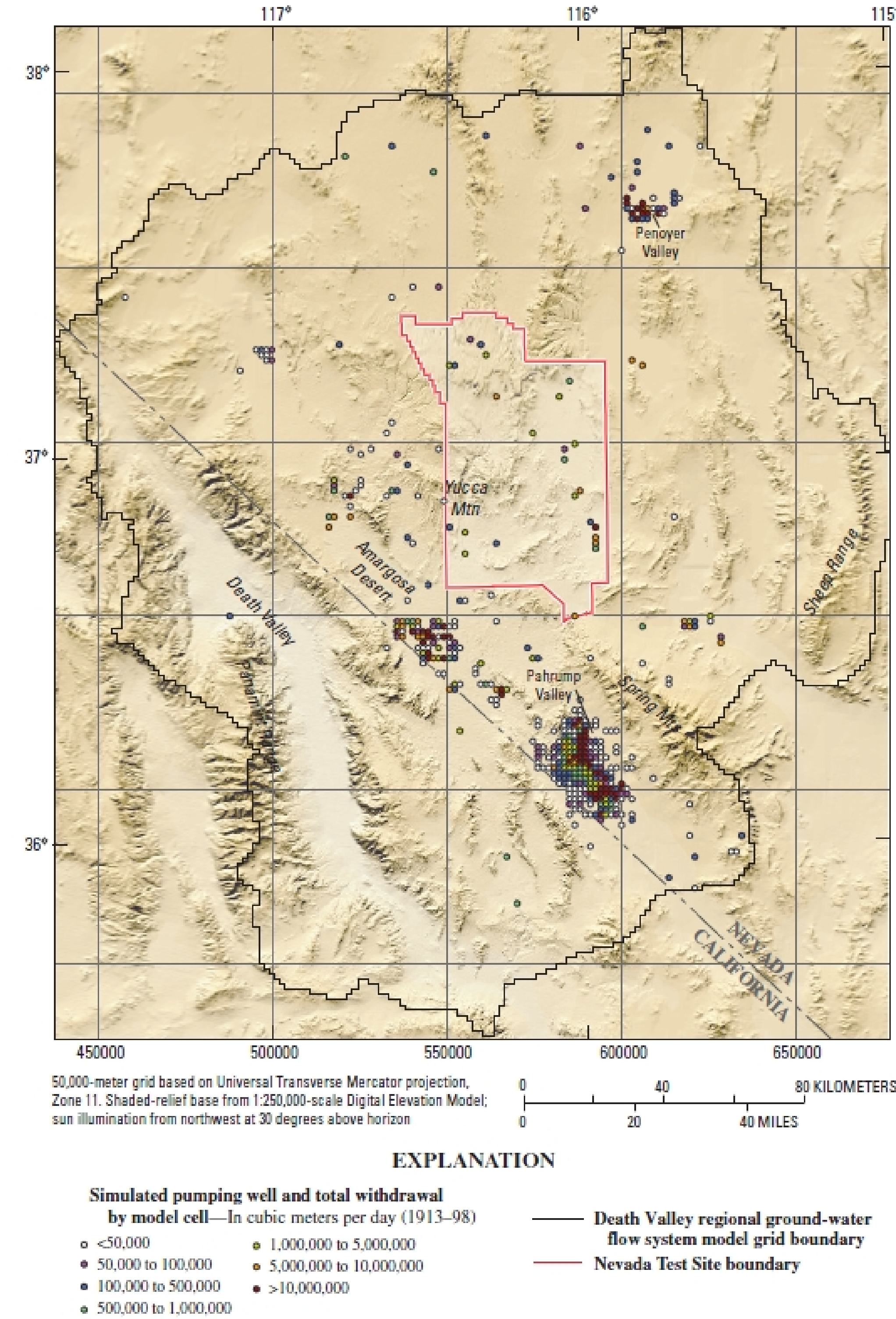

Figure 2-4. Pumping Locations in the Belcher (2004) Death Valley Regional Groundwater Flow Model (Faunt, et al., 2004b, Figure F–9)

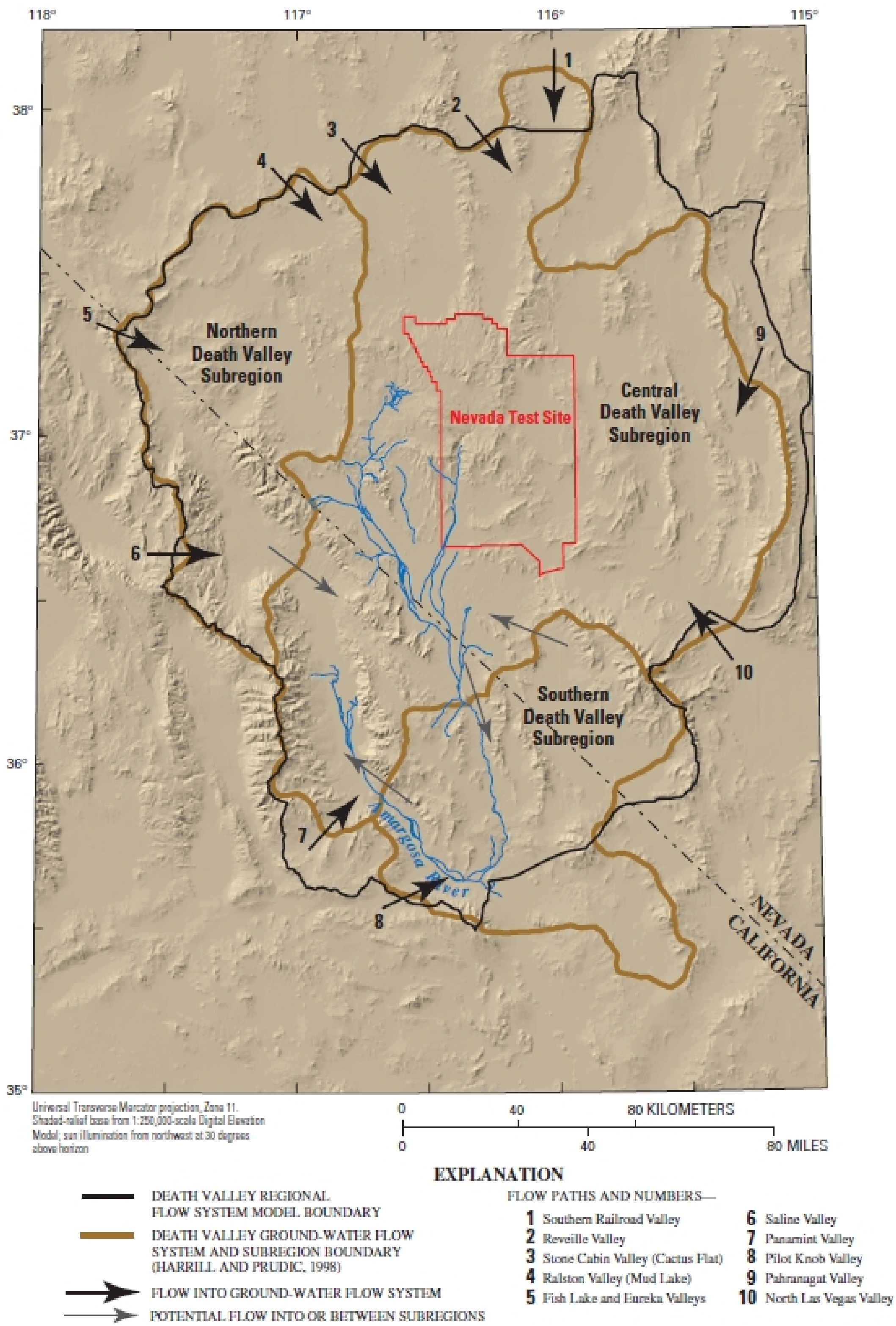

Figure 2-5. Interpreted Subregions, Groundwater Basins, and Associated Flow Paths of the Death Valley Regional Groundwater Flow System (D'Agnese, et al., 2002, Figure 7)

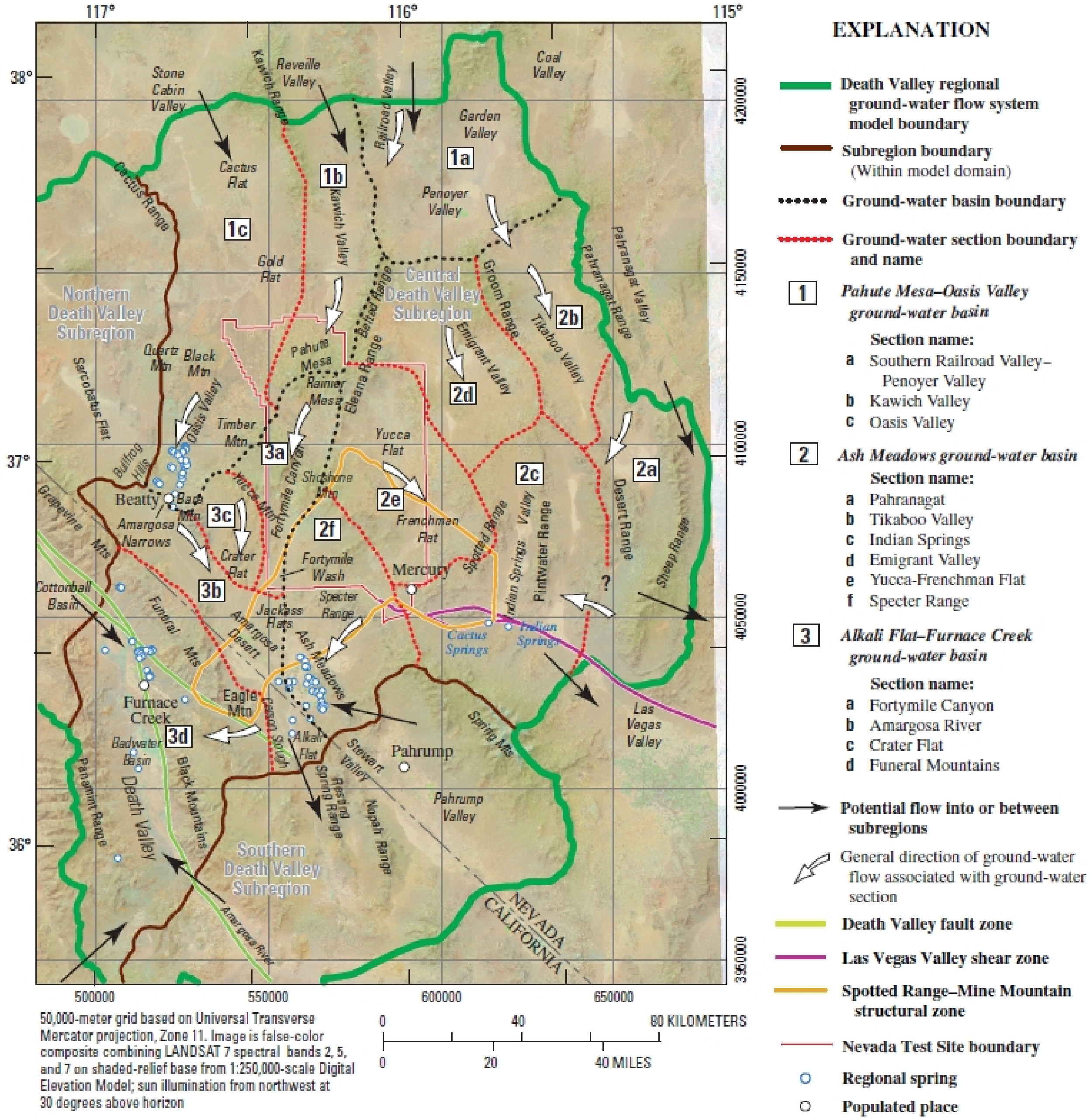

Figure 2-6. Central Death Valley Subregion of the Death Valley Regional Groundwater Flow System Showing Groundwater Basins, Sections, and Flow Directions (Faunt, et al., 2004a, Figure D-7)

flow systems and were based on location of recharge areas; regional hydraulic gradients; distribution of aquifers, structures, and confining units; location of major discharge areas, and hydrochemical composition of groundwater (Faunt, et al., 2004a).

The Alkali Flat-Furnace Creek basin includes Fortymile Canyon, the Amargosa River, Crater Flat, and Funeral Mountains. Groundwater originates as recharge on Pahute Mesa, Timber and Shoshone Mountains, and the Grapevine and Funeral Mountains, and as throughflow from Sarcobatus Flat, Oasis Valley, and Ash Meadows (Figures 2-6 and 2-7). Groundwater flows through volcanic-rock aquifers in the north and basin-fill and carbonate-rock aquifers in the south toward discharge areas in the southern and southwestern parts of the basin (Faunt, et al., 2004a). Discharge is mainly through the springs in the Furnace Creek area, with some water discharging at Ash Meadows springs (Faunt, et al., 2004a). Furnace Creek and Ash Meadows springs have similar hydrochemistry suggesting a hydraulic connection between these areas (Faunt, et al., 2004a), or perhaps a similar source region. Spring discharge is via large-scale fractures or channels in the carbonate-rock aquifer (Winograd and Pearson, 1976). Farther downgradient, groundwater, including reinfiltrated spring flow, is either transpired by mesquite on the lower part of the Furnace Creek fan, or is evaporated from the saltpan in Badwater Basin (Faunt, et al., 2004a), the lowest elevation in North America at 86 m [282 feet] below sea level.

The following four paragraphs are summarized from Faunt, et al. (2004a). The Fortymile Canyon and Fortymile Wash section is recharged predominantly by throughflow from volcanic rocks of eastern Pahute Mesa and western Rainier Mesa. Another source of local recharge is infiltration of surface runoff in the alluvium of Fortymile Canyon and Fortymile Wash during moderate to intense precipitation. Groundwater flows south from eastern Pahute Mesa and western Rainier Mesa. There are insufficient data to evaluate whether flow continues south beneath Timber Mountain or is redirected toward Shoshone Mountain, Yucca Mountain, and Jackass Flats. At Yucca Mountain, hydraulic gradients are directed upward in the volcanic-rock units from the carbonate aquifer. Flow continues south as throughflow from Fortymile Wash into the Amargosa River section.

An important source of recharge to the Amargosa River section is from throughflow in basin-fill sediments from the Oasis Valley, Crater Flat, Fortymile Canyon and Wash, and Specter Range sections. The carbonate-rock aquifer is recharged by throughflow from the Specter Range and Fortymile Canyon and Wash sections. In the northwest Amargosa River section, groundwater flow is primarily lateral and downward toward the regional flow system. In the south-central portion of the basin, regional groundwater moves upward from the carbonate aquifer into the intermediate system and toward discharge areas along the Amargosa River, Carson Slough, and Alkali Flat. Water flows from the carbonate aquifer to the north and northeast and from the volcanic-rock aquifers to the north and northwest toward the Amargosa Desert. Groundwater in the Amargosa Desert is of mixed chemical composition and contains a large amount of sodium.

In the southern Amargosa Desert, hydraulic and hydrochemical data suggest that regional flow is either (i) to the southwest through fractures in southeastern Funeral Mountains toward Death Valley or (ii) to the south diverted by low-permeability quartzites of the Resting Spring Range toward the surface at Alkali Flat.

Recharge to the Funeral Mountains section is mainly from throughflow in the carbonate aquifer in the southern Funeral Mountains, with some additional throughflow from Panamint Valley and the Owlshead Mountains. Local precipitation in the Panamint Range, Black Mountains, Funeral Mountains, and Greenwater Range supports mountain-front recharge as surface water infiltrates alluvial fans circling the floor of Death Valley. The Furnace Creek area of the Alkali Flat-Furnace Creek basin is the predominant discharge area in the Funeral Mountains section.

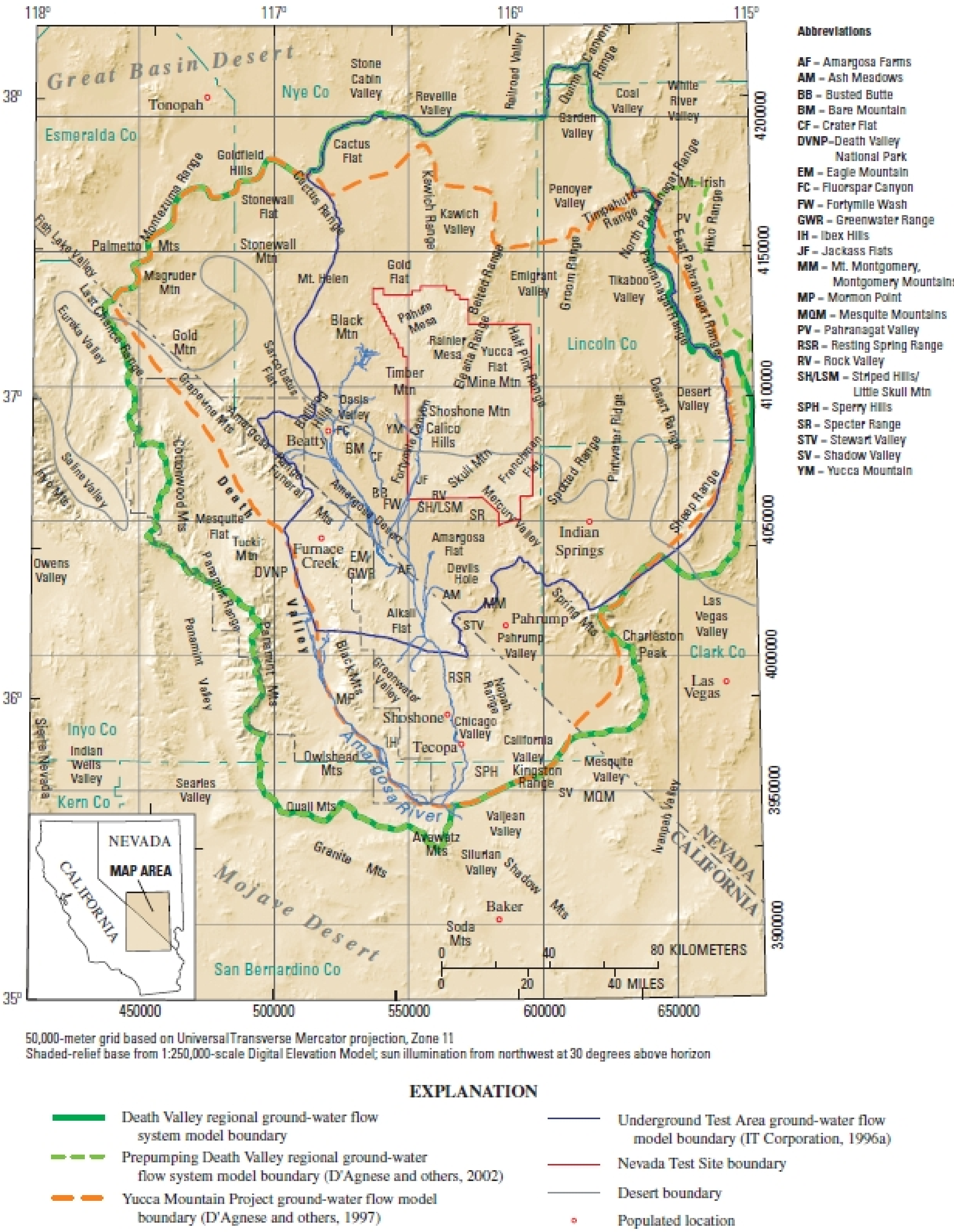

Figure 2-7. Geographic and Prominent Topographic Features of the Death Valley Regional Groundwater Flow System Region, Nevada and California (Belcher, et al., 2004, Figure A–1)

Based on the modeled directions of flow in the DVRFS, groundwater passing beneath Yucca Mountain under current conditions is most likely captured by agricultural pumping in the northern Amargosa Desert. In the absence of agricultural pumping, it is not clear whether water passing beneath Yucca Mountain would flow to the Ash Meadows area or the Badwater Basin area, as the hydraulic gradient in the southern Amargosa Desert regions is nearly flat and may be influenced by groundwater pumping. Pumping in the western Amargosa Desert for domestic, agricultural, recreational, and municipal purposes has resulted in local water level declines, and withdrawal for mining operations south of Beatty has lowered water levels in the northwestern Amargosa Desert (Faunt, et al., 2004a).

2.4 Inputs to the DOE Site-Scale Saturated Zone Flow Model for Yucca Mountain Derived From the Death Valley Regional Groundwater Flow Model

The DVRGFM model provides the hydrogeological setting for the Yucca Mountain site-scale saturated-zone flow model. The location of the Yucca Mountain model within the DVRFS model boundaries is shown in Figure 2-8. The 1997 (D'Agnese, et al., 1997), 2002 (D'Agnese, et al., 2002), and 2004 (Belcher, et al., 2004) versions of the DVRFS model supplied recharge boundary conditions to successive versions of the Yucca Mountain site-scale flow models. Distributed recharge from the DVRFS models was used for all areas of the Yucca Mountain site-scale model domain except for (i) the area beneath the unsaturated zone site-scale flow model (Wu, et al., 1997; BSC, 2004b) and (ii) the area along Fortymile Wash.

The 1997 DVRGFM lateral boundary fluxes were used as calibration targets in the initial base-case calibration of the Yucca Mountain model. Flow rates from the 2002 DVRGFM model were used in an alternate site-scale model to evaluate sensitivity to alternative interpretations (BSC, 2004a). Comparison of the Yucca Mountain site-scale model boundary flows calibrated to the 1997 versus the 2002 DVRGFM models indicated that the differences were sufficient to cause some differences in the resulting saturated zone flow fields for Yucca Mountain (BSC, 2004a). The main difference was that the alternative model calibrated to the 2002 DVRGFM targets had a relatively small net outflow from the western vertical model boundary, compared to a small net inflow for the model calibrated to the 1997 DVRGFM targets.

For the updated version of the Yucca Mountain site-scale saturated zone flow model used to support the DOE license application (Sandia National Laboratories, 2007a), the prepumped, steady-state boundary flows from the Belcher (2004) version of the DVRGFM were used as calibration. Although these boundary flux calibration targets do not include effects of current pumping, BSC (2004a) explains that the potentiometric data to which the site-scale model was calibrated represent the effects of drawdown due to pumping; the net effect of the lateral boundary flow targets is minor and local to the southwest corner of the base-case saturated zone site-scale model; and the modeled flow paths emanating from the proposed repository are virtually unchanged as a result of this calibration target.

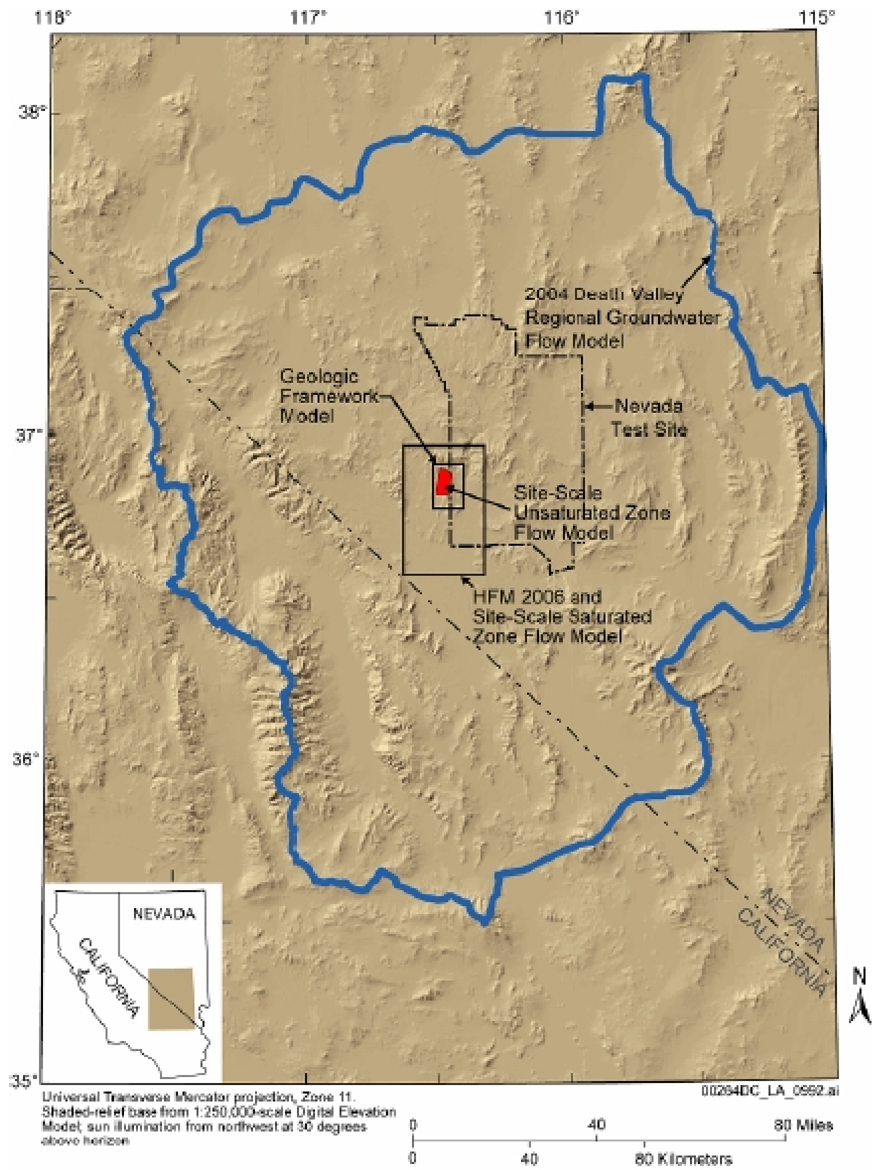

Figure 2-8. Map Showing the Boundaries of Regional and Site-Scale Models.
NOTE: HFM = Hydrogeologic Framework Model (DOE, 2008b, Figure 2.3.9-3).

3 MODELS OF THE YUCCA MOUNTAIN AREA

The following paragraphs provide brief summaries of numerical groundwater flow models for the Yucca Mountain area and some relevant supporting studies. This set of 10 bibliographic summaries is not intended to be exhaustive as there are hundreds, perhaps thousands, of publications available that document various aspects of the saturated zone flow system at the Yucca Mountain site. Rather, this section provides a list of a few key documents that chronicle the current understanding of the saturated zone flow system and would provide a useful starting point for a qualified hydrogeologist attempting to become familiar with the topic in the context of geologic disposal of nuclear waste.

Winterle, et al. (2002) documented the development of a three-dimensional, site-scale groundwater flow model for the saturated zone beneath Yucca Mountain, Nevada. The 30-layer model grid covers a 28 × 41-km [17.4 × 25.5-mi] area surrounding Yucca Mountain and explicitly includes 6 hydrostratigraphic layers and 13 structural features. The model was developed for use with the MODFLOW code using the Groundwater Modeling System, Version 3.1, user interface. Model calibrations to observed hydraulic heads were conducted by varying hydraulic conductivity values assigned to the model layers and structural features. This model is similar in scale to the DOE model used to support the Yucca Mountain license application (Sandia National Laboratories, 2007a), and the same potentiometric data were used in the calibration. The main difference from the DOE model is the assignment of hydrogeologic features, which was based on an independent interpretation of hydrostratigraphy and structure in the region. Results of the Winterle, et al. (2002) model indicate that a reasonable model calibration requires consideration of geologic structure and some type of barrier to lateral flow in the northern portion of the model and along the Solitario Canyon fault zone immediately west of Yucca Mountain. This conclusion is generally consistent with the DOE model, which also implemented low-permeability features to the north and west of the proposed repository footprint.

Winterle (2003) used the model by Winterle, et al. (2002) to evaluate the effects of conceptual model uncertainty regarding recharge and boundary conditions on calculations of saturated zone flow paths, groundwater travel times, and potential magnitudes of water table rise during future climate conditions. Four modeling case studies were presented. The results indicate that consideration of recharge over the proposed repository area can result in an order of magnitude decrease in calculated groundwater travel times for the effective porosities assumed for these modeling studies by driving flow paths deeper through more permeable pathways. Increased recharge in the model area north of Yucca Mountain and water table rise that may accompany a future wetter climate and the addition of recharge in the Fortymile Wash area did not substantially affect flow path or travel time calculations in the case studies presented in this report.

Winterle, et al. (2003) evaluated the effect of improved model calibration on the prediction of flow paths away from Yucca Mountain. The geometries and hydraulic conductivities of fault zones and HGUs were adjusted from the initial Winterle, et al. (2002) model to achieve a reduction in root-mean-square calibration error from 27 m [89 ft] in the initial model to only 1.1 m [3.6 ft] in the adjusted model. A comparison of results for the two models indicated that predicted flow paths and mean groundwater travel times were not significantly changed by the improved calibration, although the variance in groundwater travel times was somewhat less for the adjusted model.

Painter, et al. (2003) investigated a thermal anomaly pattern near the Paintbrush fault. Ground water temperatures in the fractured volcanic aquifer near Yucca Mountain, Nevada, have previously been shown to have significant spatial variability with regions of elevated temperatures coinciding roughly with near-vertical north-south trending faults. Previous investigators had suggested upwelling along faults from an underlying aquifer as a likely explanation for this ground water temperature pattern. Using a three-dimensional coupled flow and heat-transport model, they showed that the thermal high coinciding with the Paintbrush fault zone can be explained without significant upwelling from the underlying aquifer. Instead, the thermal anomaly could be explained by thermal conduction enhanced slightly by vertical ground water movement within the volcanic aquifer sequence.

Winterle (2005) developed a model for future wetter climate conditions—an extension of one of the modeling cases in Winterle (2003)—to evaluate the effects of water table rise during potential future wetter climate conditions. Water table rise was included in the model by increasing potentiometric head values at the model side boundaries by a fixed percentage and doubling the rate of surface recharge. A 5-percent increase in boundary heads from the estimated present-day values caused the calculated water table elevation to first reach the land surface in an area coincident with evaporite deposits that indicate the past occurrence of spring flows. To model their effect on flow paths, spring discharges were simulated using the MODFLOW DRAIN package, total spring discharge was varied by using different values for drain conductance and elevation. Particle-tracking analyses of flow paths from beneath Yucca Mountain were then performed for different spring discharge rates. The modeling analysis included maximum spring discharge in excess of 10,000 m^3/d [3,000 acre-ft/yr] from the area of observed evaporite deposits. Results suggest that calculated flow paths from beneath Yucca Mountain do not change appreciably as a result of spring discharges at this location. Reverse particle tracking indicated that simulated spring discharges at this location originate from the Crater Flat area, west of Yucca Mountain.

Inyo County (2006) conducted studies to evaluate potential groundwater transport pathways from the Yucca Mountain region into Inyo County, California, including Death Valley, and to evaluate the connection between the regional lower carbonate aquifer (LCA) and the biosphere. This work included a cooperative drilling program to better characterize the potential for interbasin flow through the LCA. Inyo County was interested in the LCA because (i) the upward gradient in the LCA at Yucca Mountain provides a natural barrier to radionuclide transport; (ii) the LCA is a necessary habitat resource for the endangered Devil's Hole pup fish; and (iii) the LCA is the primary water supply and source of water to the major springs in Death Valley National Park. The results of geophysical surveys, combined with the geological framework model of the region, were used to site three exploratory monitoring wells that penetrate the LCA. A numerical groundwater model of the LCA through the Southern Funeral Mountain range was developed to demonstrate potential flow through spillways in the LCA through the Southern Funeral Mountain Range. A second numerical groundwater model of the water table aquifer system at the Texas and Travertine Spring complexes was developed to simulate the potential effect of water production wells on spring flows. According to Inyo County (2006), this second model indicated that impacts of pumping on spring flows in this area would not be significant.

Sandia National Laboratories (2007a) documents the Yucca Mountain site-scale saturated zone flow model. This three dimensional model was developed using the FEHM Version 2.24 software and is the culmination of an iterative process of model development spanning more than 15 years. DOE used this model to describe the steady-state flow of groundwater as it moves from the water table below the proposed repository, through the saturated zone, and to the accessible environment in its flow and transport model abstraction of the total-system performance assessment for the license application (DOE, 2008b). The model grid is composed of 500-m [1,640 ft] square cells oriented in a north-south and east-west direction. The model domain was selected to be: (i) coincident with grid cells of the DVRGFM where site-scale model nodes correspond to regional model cell corners in the horizontal plane; (ii) sufficiently large to reduce the effects of boundary conditions on estimating permeabilities and calculated flow fields near Yucca Mountain; (iii) sufficiently large to assess groundwater flow at distances beyond the 18-km [11.2-mi] compliance boundary from the proposed repository area; (iv) small enough to minimize the model size for computational efficiency and to include structural feature detail affecting flow; (v) thick enough to include part of the regional Paleozoic carbonate aquifer (the bottoms of the site- and regional-scale models are equal at −4,000 m [−13,000 ft] below sea level); and (vi) large enough to include borehole data from the Amargosa Desert at the southern end of the modeled area. The model was calibrated to match 161 hydraulic head measurements throughout the model domain, and successfully reproduces the general pattern of observed hydraulic gradients. Results indicate flow paths that converge on the Fortymile Wash area from the north, east, and west, and nearly all of the modeled flow exits the model domain through the south lateral boundary.

Sandia National Laboratories (2007b) documents the hydrogeologic framework model, referred to as HFM 2006 that was used as the basis for defining hydrogeologic layers in the Yucca Mountain site-scale saturated zone flow model. HFM 2006 provides a static three-dimensional, simplified conceptual model with geometric elements that represent the location of differentiated HGUs within the site-scale saturated zone flow model domain. Similar to the flow model, HFM 2006 was the result of a long term iterative process of data collection, interpretation, and model revision over many years.

Sandia National Laboratories (2007c) documents the results and interpretations of field experiments, mainly hydraulic and tracer testing, used to develop and validate the conceptual models for flow and radionuclide transport models in the saturated zone near Yucca Mountain. The test interpretations summarized in this document provide the technical basis for most of the flow and transport input parameter distributions used in the total system performance assessment for the license application. Information is also provided to facilitate traceability of data sources.

Sun and Bertetti (2007) summarized numerical model experiments conducted at the Center for Nuclear Waste Regulatory Analyses to quantify the effects of subgrid physical and chemical heterogeneities in saturated alluvium of Fortymile Wash, south of Yucca Mountain. Monte Carlo simulations were performed using realizations of a fine-scale block model for which the properties are generated stochastically based on a hierarchical alluvium facies model. The results indicated that the upscaled block hydraulic conductivities have similar magnitudes as those assigned to the alluvium in site-scale models, which has grid blocks that are 500 m [1,600 ft]. The simulated longitudinal macrodispersivities at the scale of a model grid block were on the order of 10 m [32.8 ft], depending on the variance of hydraulic conductivities. The results of reactive transport modeling showed that retardation introduces at most a two-fold increase in solute spread in the longitudinal direction. Additional sensitivity studies show that including correlation in surface area normalized distribution coefficient may reduce the amount of plume spread caused by chemical heterogeneity.

Sun, et al. (2008) evaluated data from field investigations and borehole cuttings logs to develop a three-dimensional hydrofacies model of the sedimentary architecture of the alluvium deposits in Fortymile Wash, Nevada, using a hierarchical transition probability geostatistical approach. This alluvial aquifer comprises a segment of the groundwater flow pathway from the proposed high-level nuclear waste repository at Yucca Mountain, Nevada to the downstream accessible environment. This work demonstrated the link between the alluvium spatial variability and solute dispersion at different spatiotemporal scales using the stochastic-Lagrangian transport theory. They showed that, over a scale of several kilometers, the longitudinal macrodispersivity continues to increase and can be on the order of hundreds to thousands of meters, and it may not reach its asymptotic value until after 1,000 years of travel time.

4 REFERENCES

Belcher, W.R., ed. "Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model." U.S. Geological Survey Scientific Investigations Report 2004–5205. 408 pp. 2004.

Belcher, W.R., F.A. D'Agnese, and G.M. O'Brien. "Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model—Chapter A. Introduction." U.S. Geological Survey Scientific Investigations Report 2004–5205. pp. 7–19. 2004.

Belcher, W.R. and D.S. Sweetkind, eds. "Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model." U.S. Geological Survey Professional Paper 1711. 398 pp. 2010.

BSC. "Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model." ANL–NBS–MD–000010. Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004a.

———. "UZ Flow Models and Submodels." MDL–NBS–HS–000006. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004b.

D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, W.R. Belcher, and C. San Juan. "A Three-Dimensional Numerical Model of Predevelopment Conditions in the Death Valley Regional Groundwater Flow System, Nevada and California." U.S. Geological Survey Water-Resources Investigations Report 02–4102. 114 pp. 2002.

D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, and C.A. San Juan. "Simulated Effects of Climate Change on the Death Valley Regional Ground-Water Flow System, Nevada and California." U.S. Geological Survey Water-Resources Investigations Report 98-4041. 40 pp. 1999.

D'Agnese, F.A., C.C. Faunt, A.K. Turner, and M.C. Hill. "Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Groundwater Flow System, Nevada and California." U.S. Geological Survey Water-Resources Investigations Report 96-4300. 124 pp. 1997.

DOE. DOE/RW–0573, "Yucca Mountain Repository License Application, General Information Vol. 1." Update No. 1. Docket No. 63-001. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2008a.

———. DOE/RW–0573, "Yucca Mountain Repository License Application, Safety Analysis Report Vol. 14, Chapter 2, Sections 2.3.9–2.3.11." Update No. 1. Docket No. 63-001. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2008b.

Faunt, C.C., F.A. D'Agnese, and G.M. O'Brien. "Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model— Chapter D: Hydrology." U.S. Geological Survey Scientific Investigations Report 2004-5205. pp. 141–163. 2004a.

Faunt, C.C., J.B. Blainey, M.C. Hill, F.A. D'Agnese, and G.M. O'Brien. "Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model— Chapter F: Transient Numerical Model." U.S. Geological Survey Scientific Investigations Report 2004-5205. pp. 265–352. 2004b.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. "MODFLOW-2000, the U.S. Geological Survey Modular Groundwater Model—User Guide to Modularization Concepts and the GroundWater Flow Process." U.S. Geological Survey Open-File Report 00-92. 121 pp. 2000.

Hill, M.C. "A Computer Program (MODFLOWP) for Estimating Parameters of a Transient, Three-Dimensional, Groundwater Flow Model Using Nonlinear Regression." U.S. Geological Survey Open-File Report 91-484. 358 pp. 1992.

Inyo County. "Death Valley Lower Carbonate Aquifer Monitoring Program—Wells Down Gradient of the Proposed Yucca Mountain Nuclear Waste Repository." U.S. Department of Energy Cooperative Agreement DE–FC08–02RW12162 Final Project Report. Inyo County, California: Inyo County Yucca Mountain Repository Office. 2006.

IT Corporation. "Underground Test Area Subproject, Phase I, Data Analysis Task, Volume VI—Groundwater Flow Model Data Documentation Package." Report ITLV/10972–181. Las Vegas, Nevada: IT Corporation. 1996.

Mifflin, M.D. "Chapter 8: Region 5, Great Basin." *The Geology of North America*. *Vol. O-2. Hydrogeology.* W. Back, J.S. Rosenshein, and P.R. Seaber, eds. Boulder, Colorado: The Geological Society of America. pp. 69–78. 1988.

Painter, S., J. Winterle, and A. Armstrong. "Using Temperature to Test Models of Flow Near Yucca Mountain, Nevada." *Ground Water*. Vol. 41, No. 5. pp. 657–666. 2003.

Sandia National Laboratories. "Saturated Zone Site-Scale Flow Model." MDL–NBS–HS–000011. Rev. 03. Albuquerque, New Mexico: Sandia National Laboratories. 2007a.

———. "Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model." MDL–NBS–HS–000024. Rev. 01. Albuquerque, New Mexico: Sandia National Laboratories. 2007b.

———. "Saturated Zone *In-Situ* Testing." ANL–NBS–HS–000039. Rev. 02. Albuquerque, New Mexico: Sandia National Laboratories. 2007c.

Sun, A.Y. and F.P. Bertetti. "Evaluation of the Effects of Physical and Chemical Heterogeneities on Flow and Transport in the Saturated Alluvium of Fortymile Wash, Nevada." San Antonio, Texas: CNWRA. 2007.

Sun, A.Y., R, Ritzi, and D.W. Sims. "Characterization and Modeling of Spatial Variability in a Complex Alluvial Aquifer: Implications on Solute Transport." *Water Resources Research.* Vol. 44. W04402, doi:10.1029/2007WR006119. 2008

Sweetkind, D.S., W.R. Belcher, C.C. Faunt, and C.J. Potter. “Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Mmodel—Chapter B: Geology and Hydrogeology.” U.S. Geological Survey Scientific Investigations Report 2004-5205. pp. 27–98. 2004.

Winograd, I.J. and F.J. Pearson, Jr. “Major Carbon-14 Anomaly in a Regional Carbonate Aquifer—Possible Evidence for Megascale Channeling, South-Central Great Basin.” *Water Resources Research.* Vol. 12. pp. 1,125–1,143. 1976.

Winograd, I.J. and W. Thordarson. “Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada–California With Special Reference to the Nevada Test Site: Hydrology of Nuclear Test Sites.” U.S. Geological Survey Professional Paper 712-C. 1975.

Winterle, J.R., M.E. Hill, and C. Manepally. “Concepts of Saturated Zone Modeling for Development of a Site-Scale Groundwater Flow Model for Yucca Mountain.” San Antonio, Texas: CNWRA. 2002.

Winterle, J.R. “Simulation of Spring Flows South of Yucca Mountain, Nevada, Following a Potential Future Water Table Rise.” San Antonio, Texas: CNWRA. 2005.

———. “Evaluation of Alternative Concepts for Saturated Zone Flow: Effects of Recharge and Water Table Rise on Flow Paths and Travel Times at Yucca Mountain.” San Antonio, Texas: CNWRA. 2003.

Winterle, J.R., A. Claisse, and H.D. Arlt. “An Independent Site-Scale Groundwater Flow Model for Yucca Mountain.” Proceedings of the 10th International High-Level Radioactive Waste Management Conference (IHLRWM), Las Vegas, Nevada, March 30–April 2, 2003. La Grange Park, Illinois: American Nuclear Society. pp. 151–158. 2003.

Wittmeyer, G. and D. Turner. “Conceptual and Mathematical Models of the Death Valley Regional Groundwater Flow System.” San Antonio, Texas: CNWRA. 1995.

Wu, Y.S., A.C. Ritcey, C.F. Ahlers, A.K. Mishra, J.J. Hinds, and G.S. Bodvarsson. “Providing Base-Case Flow Fields for TSPA-VA: Evaluation of Uncertainty of Present-Day Infiltration Rates Using DKM/Base-Case and DKM/Weeps Parameter Sets.” Milestone SLX01LB2. ML19980501.0475. Berkeley, California: Lawrence Berkeley National Laboratory. 1997.