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U.S. Department of Energy
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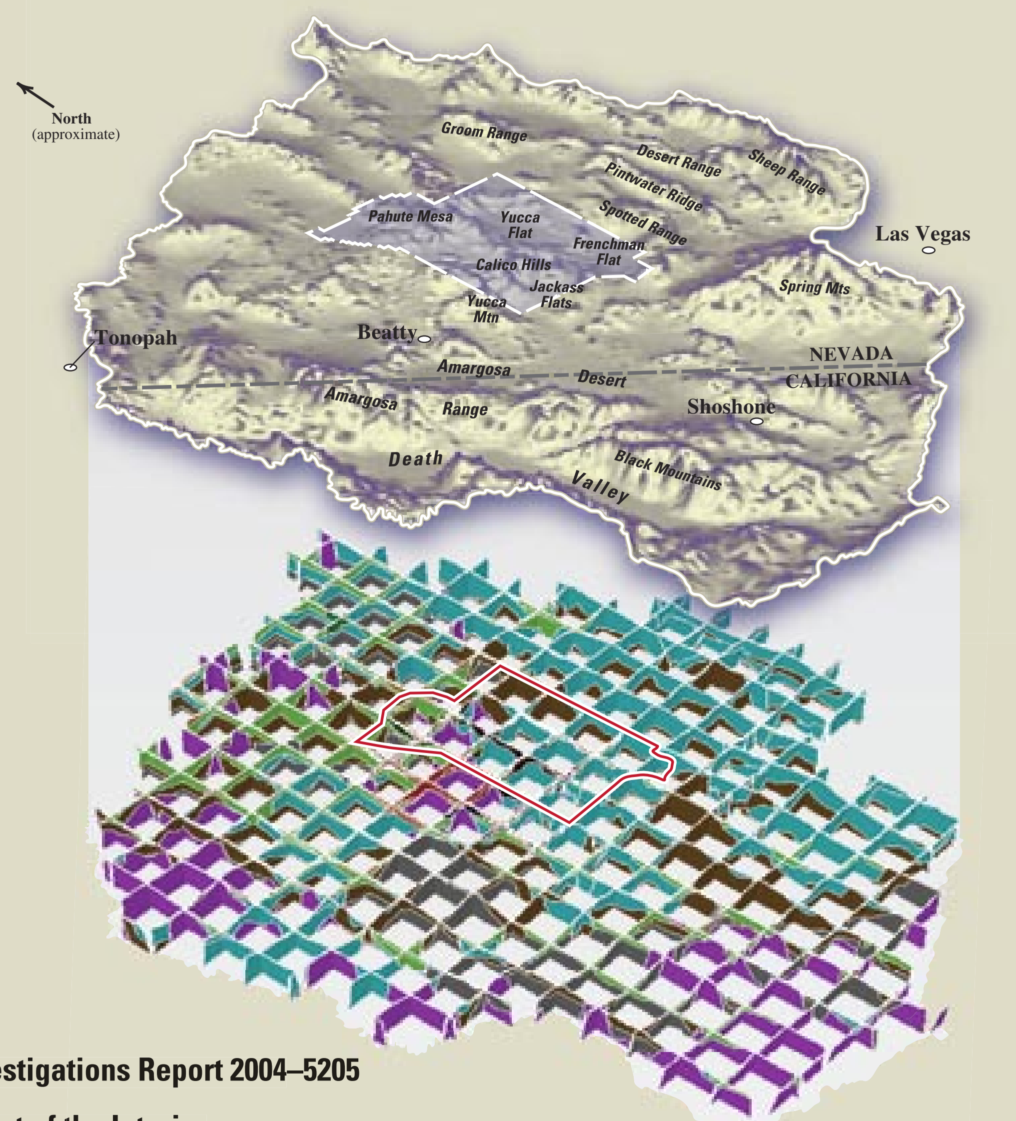
Death Valley Regional Ground-Water Flow System, Nevada and California—Hydrogeologic Framework and Transient Ground-Water Flow Model



Scientific Investigations Report 2004–5205

U.S. Department of the Interior
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U.S. Department of the Interior
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U.S. Department of the Interior
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As the editor, I have not worked with a finer team——the authors, supporting scientists, technical staff, and publications staff. Over the many years of this project, the efforts of many people have contributed to this final report. The teamwork of authors, scientists, and technical staff from many disciplines; 20 report reviewers, including Chester Zenone with a final review; and the publications staff has enabled the completion of this final report on the Death Valley regional ground-water flow system. A few lines from Tennyson's "Ulysses" express my deep gratitude for the hard work and dedication of all of the people involved over the years of this project:

> Tho' much is taken, much abides; and tho'
> We are not now that strength which in the old days
> Moved earth and heaven; that which we are, we are;
> One equal-temper of heroic hearts,
> Made weak by time and fate, but strong in will
> To strive, to seek, to find, and not to yield.

Contents

Plates

Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot
million cubic meters (Mm^3)	35.31	million cubic feet
meter per day (m/d)	3.281	foot per day
millimeter per year (mm/yr)	0.03937	inch per year
meter per year (m/yr)	3.281	foot per year
meter squared per day (m^2/d)	10.76	square foot per day
cubic meter per day (m^3/d)	35.31	cubic foot per day
cubic meter per day (m^3/d)	264.2	gallon per day
cubic meter per year (m^3/yr)	35.31	cubic foot per year
meter per day per meter (m/d/m)	1	foot per day per foot

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

2D	Two-dimensional
3D	Three-dimensional
AA	Alluvial aquifer
ACU	Alluvial confining unit
BRU	Belted Range unit
CAU	Corrective Action Unit
CFBCU	Crater Flat–Bullfrog confining unit
CFPPA	Crater Flat–Prow Pass aquifer
CFTA	Crater Flat–Tram aquifer
CHVU	Calico Hills volcanic-rock unit
CSS	Composite scaled sensitivity
CV	Coefficient of variation
DEM	Digital elevation model
DOE	U.S. Department of Energy
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DRN	Drain
DSS	Dimensionless scaled sensitivity
DVRFS	Death Valley regional ground-water flow system
ECU	Eleana confining unit
EM	Office of Environmental Management
ERD	Environmental Restoration Division

ET	Evapotranspiration
EWDP	Early Warning Drilling Program
FWS	U.S. Fish and Wildlife Service
Ga	Giga-annum (billion years ago)
GFM	Geologic framework model
GIS	Geographic information system
GPS	Global positioning system
GWSI	Ground-Water Site Inventory
HFB	Horizontal flow barrier
HFM	Hydrogeologic framework model
HG	Hydrograph
HGU	Hydrogeologic unit
HRMP	Hydrologic Resource Management Program
HUF	Hydrogeologic-unit flow
ICU	Intrusive-rock confining unit
K	Hydraulic conductivity
ka	Thousand years ago
K-Ar	Potassium-argon
LA	Limestone aquifer
LCA	Lower carbonate-rock aquifer
LCA_T1	Lower carbonate-rock thrust
LCCU	Lower clastic-rock confining unit
LCCU_T1	Lower clastic-rock confining unit thrust
LFU	Lava-flow unit
LOTR	Line of transient regression
LVVSZ	Las Vegas Valley shear zone
LVVWD	Las Vegas Valley Water District
Ma	Mega-annum (million years ago)
MNW	Multi-node well
Mvs	Mesozoic volcanics and sedimentary rock unit
NAD 27	North American Datum of 1927
NAVD 88	North American Vertical Datum of 1988
NDWR	Nevada Division of Water Resources
NNSA	National Nuclear Security Administration
Nobs	Number of observations
NPS	National Park Service
NSO	Nevada Site Office
NTS	Nevada Test Site
NWIS	National Water Information System
OAA	Older alluvial aquifer
OACU	Older alluvial confining unit
OCRWM	Office of Civilian Radioactive Waste Management
ORD	Office of Repository Development
OVU	Older volcanic-rock unit
P1	Lower clastic confining unit

P2	Regional carbonate aquifer
PCC	Parameter correlation coefficient
PMOV	Pahute Mesa–Oasis Valley
PVA	Paintbrush volcanic-rock aquifer
SCCC	Silent Canyon caldera complex
SCU	Sedimentary-rock confining unit
sd	Standard deviation
SOSWR	Sum of squared weighted residuals
SWNVF	Southwestern Nevada volcanic field
TBA	Belted Range aquifer
TBCU	Basal confining unit
TBQ	Basal aquifer
TC	Paintbrush/Calico Hills tuff cone unit
TCB	Bullfrog confining unit
TMA	Timber Mountain aquifer
TMCC	Timber Mountain caldera complex
TMVA	Thirsty Canyon–Timber Mountain volcanic-rock aquifer
TSDVS	Tertiary sediments–Death Valley sediments
Tv	Tertiary volcanic-rock unit
UCA	Upper carbonate-rock aquifer
UCCU	Upper clastic-rock confining unit
UGTA	Underground Test Area
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VA	Volcanic-rock aquifer
VCU	Volcanic-rock confining unit
VSU	Volcanic- and sedimentary-rock unit
VU	Volcanic rocks undifferentiated
WVU	Wahmonie volcanic-rock confining unit
XCU	Crystalline-rock confining unit
YAA	Younger alluvial aquifer
YACU	Younger alluvial confining unit
YMP	Yucca Mountain Project
YVU	Younger volcanic-rock unit

Death Valley Regional Ground-Water Flow System, Nevada and California—Hydrogeologic Framework and Transient Ground-Water Flow Model

Edited by Wayne R. Belcher

Abstract

A numerical three-dimensional (3D) transient ground-water flow model of the Death Valley region was developed by the U.S. Geological Survey for the U.S. Department of Energy programs at the Nevada Test Site and at Yucca Mountain, Nevada. Decades of study of aspects of the ground-water flow system and previous less extensive ground-water flow models were incorporated and reevaluated together with new data to provide greater detail for the complex, digital model.

A 3D digital hydrogeologic framework model (HFM) was developed from digital elevation models, geologic maps, borehole information, geologic and hydrogeologic cross sections, and other 3D models to represent the geometry of the hydrogeologic units (HGUs). Structural features, such as faults and fractures, that affect ground-water flow also were added. The HFM represents Precambrian and Paleozoic crystalline and sedimentary rocks, Mesozoic sedimentary rocks, Mesozoic to Cenozoic intrusive rocks, Cenozoic volcanic tuffs and lavas, and late Cenozoic sedimentary deposits of the Death Valley regional ground-water flow system (DVRFS) region in 27 HGUs.

Information from a series of investigations was compiled to conceptualize and quantify hydrologic components of the ground-water flow system within the DVRFS model domain and to provide hydraulic-property and head-observation data used in the calibration of the transient-flow model. These studies reevaluated natural ground-water discharge occurring through evapotranspiration (ET) and spring flow; the history of ground-water pumping from 1913 through 1998; ground-water recharge simulated as net infiltration; model boundary inflows and outflows based on regional hydraulic gradients and water budgets of surrounding areas; hydraulic conductivity and its relation to depth; and water levels appropriate for regional simulation of prepumped and pumped conditions within the DVRFS model domain. Simulation results appropriate for the regional extent and scale of the model were provided by acquiring additional data, by reevaluating existing data using current technology and concepts, and by refining earlier interpretations to reflect the current understanding of the regional ground-water flow system.

Ground-water flow in the Death Valley region is composed of several interconnected, complex ground-water flow systems. Ground-water flow occurs in three subregions in relatively shallow and localized flow paths that are superimposed on deeper, regional flow paths. Regional ground-water flow is predominantly through a thick Paleozoic carbonate rock sequence affected by complex geologic structures from regional faulting and fracturing that can enhance or impede flow. Spring flow and ET are the dominant natural ground-water discharge processes. Ground water also is withdrawn for agricultural, commercial, and domestic uses.

Ground-water flow in the DVRFS was simulated using MODFLOW-2000, a 3D finite-difference modular ground-water flow modeling code that incorporates a nonlinear least-squares regression technique to estimate aquifer parameters. The DVRFS model has 16 layers of defined thickness, a finite-difference grid consisting of 194 rows and 160 columns, and uniform cells 1,500 meters (m) on each side.

Prepumping conditions (before 1913) were used as the initial conditions for the transient-state calibration. The model uses annual stress periods with discrete recharge and discharge components. Recharge occurs mostly from infiltration of precipitation and runoff on high mountain ranges and from a small amount of underflow from adjacent basins. Discharge occurs primarily through ET and spring discharge (both simulated as drains) and water withdrawal by pumping and, to a lesser amount, by underflow to adjacent basins, also simulated by drains. All parameter values estimated by the regression are reasonable and within the range of expected values. The simulated hydraulic heads of the final calibrated transient model generally fit observed heads reasonably well (residuals with absolute values less than 10 m) with two exceptions: in most areas of nearly flat hydraulic gradient the fit is considered moderate (residuals with absolute values of 10 to 20 m), and in areas of steep hydraulic gradient, such as Indian Springs, western Yucca Flat, and the southern part of the Bullfrog Hills, the fit is poor (residuals with absolute values greater than 20 m). Ground-water discharge residuals are fairly random, with as many areas where simulated flows are less than observed flows as areas where simulated flows are greater. The highest unweighted ground-water discharge residuals occur at Death

Valley and Ash Meadows. High weighted discharge residuals were computed in the Pahrump Valley, possibly indicating a poor definition of hydraulic properties or discharge estimates in that area.

The model represents the large and complex ground-water flow system of the Death Valley region at a greater degree of refinement and accuracy than has been possible previously. The representation of detail provided by the 3D digital hydrogeologic framework model and the numerical ground-water flow model enabled greater spatial accuracy in every model parameter. The lithostratigraphy and structural effects of the hydrogeologic framework; recharge estimates from simulated net infiltration; discharge estimates from ET, spring flow, and pumping; and boundary inflow and outflow estimates all were reevaluated, some additional data were collected, and accuracy was improved. Uncertainty in the results of the flow model simulations can be reduced by improving on the quality, interpretation, and representation of the water-level observations used to calibrate the model and improving on the representation of the HGU geometries, the spatial variability of HGU material properties, the flow model physical framework, and the hydrologic conditions.

View from Mount Stirling (2,506 m) in the Spring Mountains to the northeast toward the Pintwater, Desert, and Sheep Ranges. The Las Vegas Valley shear zone runs across the middle of the photograph between the Spring Mountains and the mountain ranges to the north. Playas are visible in Indian Springs Valley (toward the west or left side of the photograph) and in Three Lakes Valley (to the east or the right side of the photograph). Indian Springs Air Force Base is visible in the center foreground, at the base of the Pintwater Range. Photograph by Nancy A. Damar, U.S. Geological Survey.

Introduction

By Wayne R. Belcher, Frank A. D’Agnese, and Grady M. O’Brien

Chapter A of

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CHAPTER A. Introduction

By Wayne R. Belcher, Frank A. D'Agnese, and Grady M. O'Brien

In the early 1990's, two numerical models of the Death Valley regional ground-water flow system (DVRFS) were developed by the U.S. Department of Energy (DOE) to support investigations at the Nevada Test Site (NTS), where nuclear tests were conducted from 1951 to 1992, and at Yucca Mountain, Nev., the proposed geologic repository for high-level radioactive waste and spent nuclear fuel for the U.S. (fig. A–1). The model developed for the National Nuclear Security Administration/Nevada Site Office (NNSA/NSO) Underground Test Area (DOE/NV-UGTA) project of the Office of Environmental Management (EM) is designated the DOE/NV-UGTA model (IT Corporation, 1996a). The second model was developed collaboratively for the Office of Civilian Radioactive Waste Management's (OCRWM) Yucca Mountain Project (YMP) and the NNSA/NSO Hydrologic Resource Management Program (HRMP) and is designated the YMP/HRMP model (D'Agnese and others, 1997).

The DOE/NV-UGTA flow model (IT Corporation, 1996a) was developed by the EM support services contractor, HSI/GeoTrans Inc., using MODFLOW (McDonald and Harbaugh, 1988) to evaluate the transport of radionuclides from underground nuclear weapons test sites on the NTS. The YMP/HRMP model (D'Agnese and others, 1997) was developed by the U.S. Geological Survey (USGS) using MODFLOWP (Hill, 1992) to characterize the regional ground-water flow system with respect to the potential release of radionuclides from the proposed geologic high-level radioactive waste repository at Yucca Mountain.

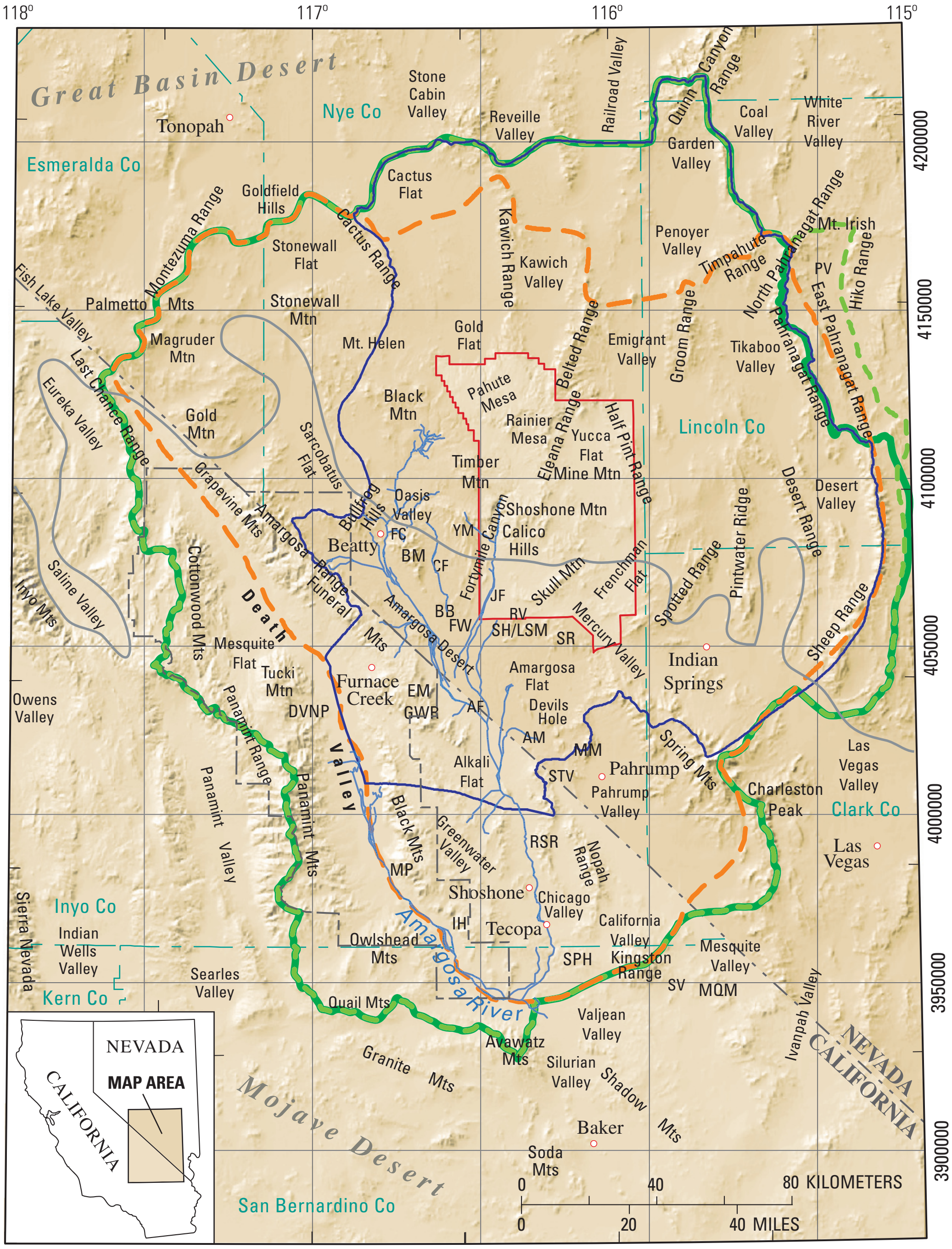
In general, the two models were based on the same hydrologic data set. However, the models differed somewhat in the details of their particular interpretations of the regional hydrogeology. Firstly, these differences were the result of the fact that the DOE/NV-UGTA model had 20 layers and encompassed areas in, adjacent to, and downgradient from the UGTAs of the NTS, whereas the YMP/HRMP model had only three layers but encompassed much of the DVRFS region. Secondly, differences between the two hydrogeologic frameworks occurred where different data sets were used or data were sparse and the results were highly interpretive. Thirdly, the hydrogeologic units used in each framework differed, especially in the Cenozoic volcanic rocks. Finally, estimates of recharge were highly interpretive and differed significantly for each flow model domain. Together, these differences likely resulted in the different ground-water flow path and flux results from the two models.

In 1998, DOE requested that the USGS begin a 5-year project to develop an improved ground-water flow model of the DVRFS to support NNSA/NSO and YMP programs. This work was done by the U.S. Geological Suvey in cooperation with the U.S. Department of Energy under Interagency Agreements DE–AI52–01NV13944 and DE–AI08–02RW12167. Newly available data and modeling tools were used and the data and results of the previous two regional-scale models were integrated to produce a single regional-scale flow model. During this effort, the USGS cooperated with other Federal, State, and local entities in the region, including the National Park Service (NPS), the Fish and Wildlife Service (FWS), the Bureau of Land Management (BLM), and county governments in Nevada and California, in order to benefit from their expertise. Many of these entities also contributed funds to this project.

Interest in the regional flow system is driven by the need to: (1) understand the ground-water flow paths and travel times associated with potential movement of radioactive material from the NTS; (2) characterize the ground-water system in the vicinity of the proposed high-level radioactive waste repository at Yucca Mountain, Nev. (Hanks and others, 1999); and (3) address a variety of potential effects on users downgradient from the NTS and Yucca Mountain, including the agricultural communities in the Amargosa Desert, the Death Valley National Park, and Native American interests.

The initial objectives of the DVRFS project included the construction and calibration of a steady-state model that represents prepumping conditions for the DVRFS. This model was intended to (1) provide a starting point for calibration of the transient ground-water flow model, (2) characterize regional three-dimensional (3D) ground-water flow paths, (3) define discharge and recharge locations, (4) estimate the magnitude of subsurface flux, and (5) represent the effects of regional geologic structural features on regional flow. The digital 3D hydrogeologic framework model (HFM) and steady-state prepumping numerical flow model are documented, respectively, in Belcher and others (2002) and D'Agnese and others (2002).

The ultimate objective of the DVRFS model project, and the subject of the chapters in this volume, is the construction and calibration of a transient model that simulates the ground-water conditions of the model domain through time. Over the long term, this model is intended to be used to (1) provide the boundary conditions for the site-scale models at Yucca Mountain and the UGTA Corrective Action Units



Abbreviations

AF = Amargosa Farms
AM = Ash Meadows
BB = Busted Butte
BM = Bare Mountain
CF = Crater Flat
DVNP=Death Valley National Park
EM = Eagle Mountain
FC = Fluorspar Canyon
FW = Fortymile Wash
GWR = Greenwater Range
IH = Ibex Hills
JF = Jackass Flats
MM = Mt. Montgomery, Montgomery Mountains
MP = Mormon Point
MQM = Mesquite Mountains
PV = Pahranagat Valley
RSR = Resting Spring Range
RV = Rock Valley
SH/LSM = Striped Hills/ Little Skull Mtn
SPH = Sperry Hills
SR = Specter Range
STV = Stewart Valley
SV = Shadow Valley
YM = Yucca Mountain

50,000-meter grid based on Universal Transverse Mercator projection, Zone 11
Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

EXPLANATION

- Death Valley regional ground-water flow system model boundary
- Prepumping Death Valley regional ground-water flow system model boundary (D'Agnese and others, 2002)
- Yucca Mountain Project ground-water flow model boundary (D'Agnese and others, 1997)
- Underground Test Area ground-water flow model boundary (IT Corporation, 1996a)
- Nevada Test Site boundary
- Desert boundary
- Populated location

Figure A–1. Geographic and prominent topographic features of the Death Valley regional ground-water flow system region, Nevada and California.

(CAUs) on the NTS, (2) evaluate the impacts of changes in system flux, regardless of whether the changes are natural or human induced, (3) provide a technical basis for decisions on the quantity of water available for defense and economic development activities on the NTS, (4) determine the potential effects of increased offsite water use on NTS water supplies, (5) provide a framework for determining effective source plume, ambient trend, and point-of-use ground-water-quality monitoring locations, and (6) facilitate the development of a cooperative, regional Death Valley ground-water management district.

Purpose and Scope

This report presents the hydrogeology, the conceptual hydrologic model, the hydrologic system inputs and outputs of the DVRFS region, and how this information is used to construct an HFM and a transient numerical ground-water flow model. The ground-water flow model simulates transient conditions from 1913 through 1998 using the modular ground-water flow model, MODFLOW-2000 (Harbaugh and others, 2000), and a simulated steady-state head distribution representing prepumping conditions (the initial conditions of the model). Transient stresses imposed on the regional ground-water flow system include ground-water pumpage that occurred from 1913 through 1998, and flows from springs affected by pumping; simulated areal recharge was held constant at average annual values.

The current understanding of regional ground-water flow in the Great Basin came from the basin studies done under the U.S. Geological Survey and the State of Nevada cooperative ground-water program. Maxey and Eakin (1949) compared recharge and discharge estimates of individual basins and realized that many basins were not closed to ground-water transfer to or from adjacent basins. Eakin (1966) identified a system of interconnected basins of the White River and Muddy River springs area. The water budget imbalances within and between basins was useful in discerning interbasin flow and defining the basins of the Colorado River flow system (formerly the White River flow system) to the east of the DVRFS. The concept of interbasin flow into the Death Valley region was first suggested by Hunt and Robinson (1960).

The DVRFS is a major regional flow system in which ground water 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, Calif. (Rush, 1968; Harrill and others, 1988). Ground-water flow in the region is strongly influenced by the complex geologic framework of the DVRFS region. Numerical modeling of the regional ground-water flow system must incorporate the 3D distribution of the principal aquifers and confining units, as well as the principal geologic structures that may affect subsurface flow.

The scope of this study can be summarized as follows:

1. The study is limited to the DVRFS region, specified as the model domain (fig. A–1).

2. The details of the hydrogeologic framework are limited to a particular interpretation of regional hydrogeologic conditions.

3. The period of simulation consists of a steady-state prepumping condition (prior to 1913) and transient condition (1913 to 1998).

4. The scale of investigation is regional, simulating features and processes that are appropriate at a 1:250,000 scale.

This report consists of six chapters that describe various aspects of the geology, hydrology, and transient simulation of the DVRFS region. Chapter A (this chapter) introduces the DVRFS transient flow modeling effort, describes the site, and outlines previous regional-scale simulations in this area. Chapter B describes the geologic and hydrogeologic framework of the DVRFS region, detailing the geologic history, the geologic and hydrogeologic units present in the region, and structural features that control regional ground-water flow. Chapter C describes various hydrologic evaluations and the basic hydrologic data of the regional ground-water flow system, including studies of recharge, evapotranspiration, spring discharge, pumpage rate, and hydraulic properties of the hydrogeologic units. Chapter D describes the hydrologic conceptual model of the region. The discussion includes the flow-system boundaries and subregions within the model area, occurrence of ground water and surface water, and paleohydrology. Chapter E describes the construction of the HFM using the stratigraphic and structural data presented in Chapter B. Finally, chapter F describes the construction and calibration of the numerical transient ground-water flow model of the DVRFS, from prepumping conditions (before 1913) to transient conditions from 1913 to 1998.

Site Description

In this report, the DVRFS region encompasses approximately 100,000 km^2 in Nevada and California and is bounded by latitudes 35°00'N and 38°15'N and by longitudes 115°00'W and 118°00'W. The DVRFS boundary has been variably defined and named in the past by several investigators (Harrill and others, 1988; Bedinger and others, 1989; D'Agnese and others, 1997; Harrill and Prudic, 1998; Bedinger and Harrill, Appendix 1, this volume) (fig. A–2). Comparison of figures A–1 and A–2 shows that the DVRFS model boundary depicted on figure A–1 differs slightly from the flow system boundaries depicted on figure A–2. Because of the various definitions of the DVRFS boundary, the simulated area is referred to as the "model domain." The region surrounding the model domain, inclusive of the model domain, is referred to as the "DVRFS region." The DVRFS is approximately that area depicted on figure A–1.

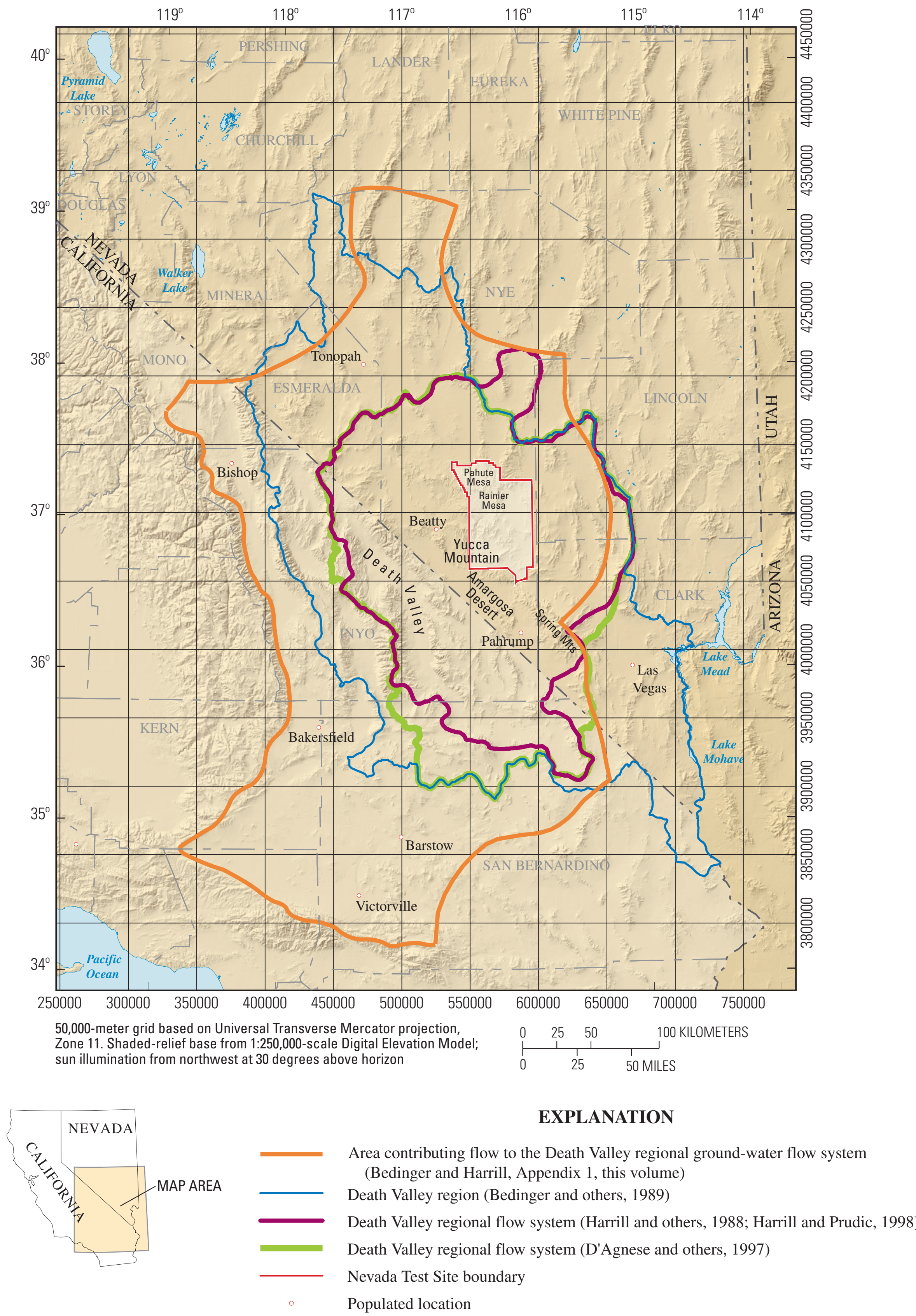


Figure A–2. Delineations of the Death Valley regional ground-water flow system.

Physiography

The DVRFS region is in the southern Great Basin, a subprovince of the Basin and Range physiographic province (Fenneman, 1931). The DVRFS region (fig. A–1) includes several large valleys, including the Amargosa Desert, Pahrump Valley, and Death Valley. The region also includes several major mountain ranges including the Spring Mountains and the Panamint, Sheep, Amargosa, Kawich, Kingston, Pahranagat, Timpahute, and Last Chance Ranges. Late Cenozoic tectonic activity accounts for much of the observed topographic relief across the DVRFS region (Grose and Smith, 1989). Altitudes range from 86 meters (m) below sea level at Death Valley to 3,600 m above sea level at Charleston Peak in the Spring Mountains. The maximum relief, 3,500 m, occurs on the west side of Death Valley. The relief between valleys and adjoining mountains locally exceeds 1,500 m (Bedinger and others, 1989). Mountain ranges in the northern one-half of the model domain trend north-south typical of the Basin and Range province, whereas principal mountain ranges in the southern one-half of the model domain trend northwest-southeast. Throughout the model domain the trends of intermediate-scale topographic features are quite variable.

Mountain ranges in the Basin and Range province typically occupy an area of about 25 percent of the total province (Peterson, 1981). The remainder is occupied by broad intermontane basins and, in the central part of the DVRFS region, a broad volcanic plateau. The basins are filled with sediment and some interbedded volcanic deposits that gently slope from the valley floors to the bordering mountain ranges (Peterson, 1981).

The valley floors are local depositional centers that usually contain playas that act as catchments for surface-water runoff (Grose and Smith, 1989). The Amargosa River (fig. A–1), an intermittent stream whose drainage basin encompasses about 15,000 km^2, discharges into the south end of the Death Valley saltpan, the largest playa in the DVRFS region (Hunt and others, 1966). Most of the basins seldom contain perennial surface water. Playas and alluvial flats lying within these intermontane basins constitute about 10 percent of the region (Bedinger and others, 1989). Many playas contain saline deposits that indicate the evaporation of surface water and(or) shallow ground water from the playa surface. Some of the playas that have been deformed by Quaternary faulting contain springs where ground water is forced to the surface by juxtaposed lacustrine and basin-fill deposits (Bedinger and others, 1989). The Amargosa Desert contains several spring pools and human-engineered reservoirs that are supported by regional ground-water discharge.

Climate

Climatic conditions in the DVRFS region vary significantly and are primarily controlled by altitude. The northern part of the region, including the Cactus, Kawich, and Timpahute Ranges (fig. A–1), forms part of the Great Basin Desert and is characterized by warm, dry summers and cold, dry winters. The southern part of the region, including Death Valley and the eastern Mojave Desert, is characterized by hot, dry summers and warm, dry winters (Benson and Darrow, 1981). The central area around the NTS has been called the Transition Desert (Beatley, 1976), which represents a mixing of the two climates (fig. A–3).

Precipitation in the region is influenced by two distinct storm patterns, one occurring in the winter and the other in the summer. Winter precipitation (dominantly snow in the mountains and rain in the valleys) tends to be of low intensity and long duration and covers great areas. In contrast, most summer rains, resulting from local convective thunderstorms, are of high intensity and short duration (Hales, 1972, 1974).

Quiring (1965) and French (1983) analyzed the distribution of precipitation resulting from the winter and summer weather regimes across southern Nevada. Quiring (1965) concluded that the two sources of precipitation (fig. A–4) affect regions south of latitude 38°30'N and primarily are orographically controlled (especially by the Sierra Nevada, fig. A–1). Because of these rain shadows, some areas of southern Nevada receive excess precipitation while other areas receive a precipitation deficit relative to mean precipitation (French, 1983).

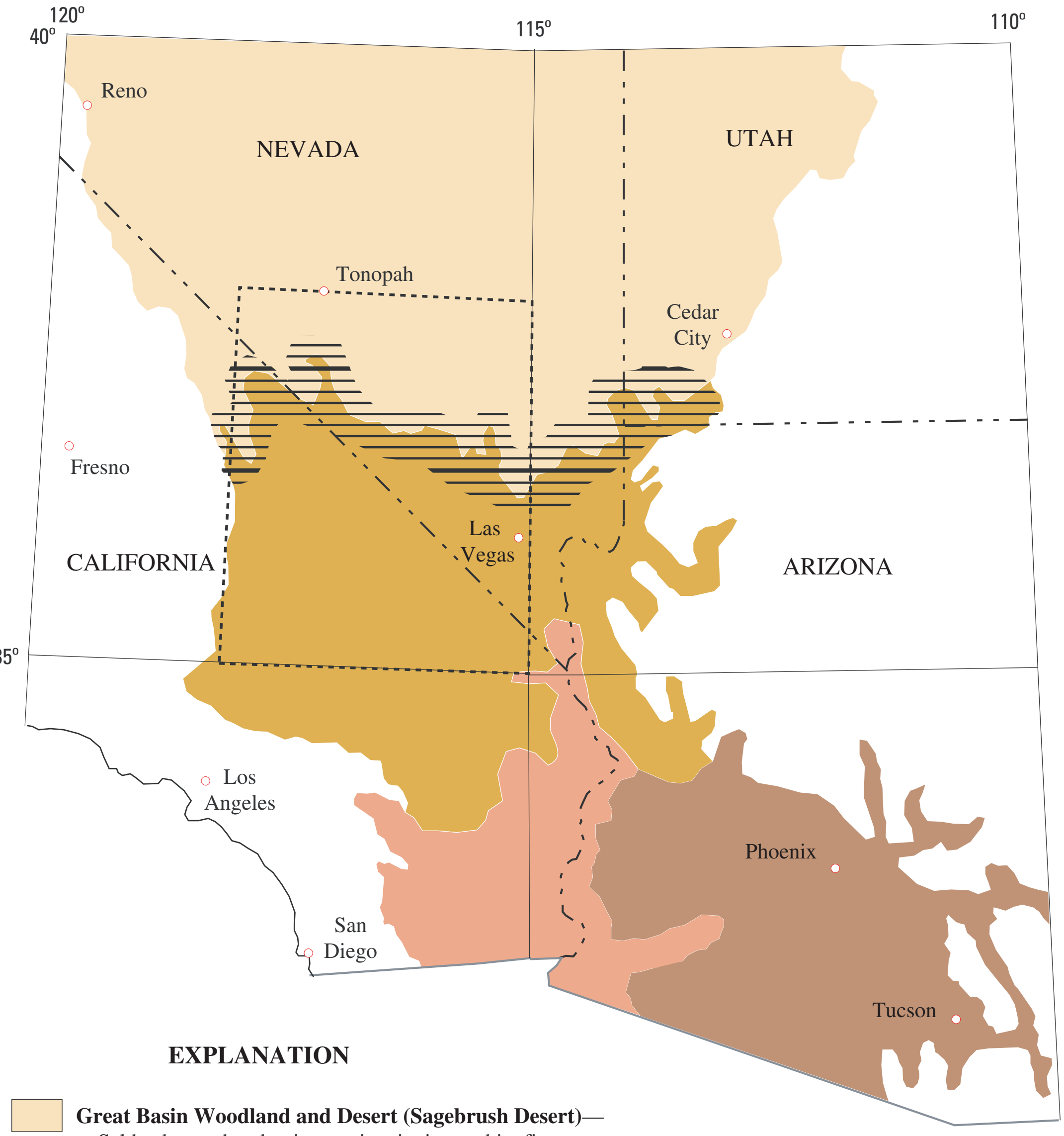
Soils and Vegetation

The soils and vegetation of the DVRFS region are controlled to a substantial degree by climatic, geomorphic, and hydrologic factors and are highly variable and complex. Soils in the DVRFS region typically include soils weathered from bedrock (lithosols) on the mountains, medium- to coarse-textured soils on alluvial fans and terraces, and fine-grained, alluvial soils on the valley floors. In general, the soils of the mountains and hills are thin and coarse textured, with little moisture-holding capacity. The soils of the alluvial fans on the upper bajadas also are coarse textured but are thicker, so that infiltration rates are relatively high. Infiltration rates of the alluvial basin soils are low because the downward movement of water commonly is impeded by calcium-carbonate-cemented layers (pedogenic carbonate), fine-grained playa deposits, and less commonly, silicified hardpans that form within the soils over time (Beatley, 1976).

Vegetation distributions in the DVRFS region are influenced by water availability and temperature and vary by latitude and altitude. Thus, vegetation communities in the region demonstrate both topographic and geographic patterns. Mixing of the cold, northern Great Basin Desert climate with the warm, southern Mojave Desert climate results in a heterogeneous distribution of plant associations (Beatley, 1976).

Land Management and Water Use

Most of the land in the DVRFS region is owned by the U.S. Government and is administered by numerous Federal agencies. Privately owned land is scattered throughout the region, but most private ownership is concentrated near the



EXPLANATION

Great Basin Woodland and Desert (Sagebrush Desert)—
Saltbush, sagebrush, pinyon pine, juniper, white fir

Transition Desert—
Creosote bush, blackbrush, hop sage, water jacket

Mojave Desert—
Creosote bush, burro weed, wolfberry, hop sage, saltbush, ash, screwbean, emory baccharis, mesquite

Colorado Sonoran Desert—
Cottonwood, ironwood, mesquite, desert willow, palo verde, creosote bush, bursage, saltbush, acacia, cholla

Arizona Sonoran Desert—
Mesquite, saguaro, palo verde, creosote bush, ocotillo, desert mariposa lily, agave, Coulter's globemarrow

Death Valley region

Populated location

Figure A–3. Desert climatic zones of the Death Valley regional ground-water flow system region.

agricultural centers of Amargosa Desert and Pahrump Valley, the mining community of Beatty, Nev., and the towns of Shoshone, Tecopa, and Baker, Calif. (fig. A–1).

The major land-use activities in the region are agriculture, livestock ranching, recreation, and mining. Water within the DVRFS region is used mostly for domestic, commercial, agricultural, livestock, military, and mining purposes. Water resources in the Amargosa Desert support biological communities protected by the National Park Service in Death Valley and by the U.S. Fish and Wildlife Service at Ash Meadows National Wildlife Refuge, such as the Devils Hole pupfish (*Cyprinidon diabolis*), whose continued existence depends on naturally occurring spring discharges and stable pool levels in Devils Hole.

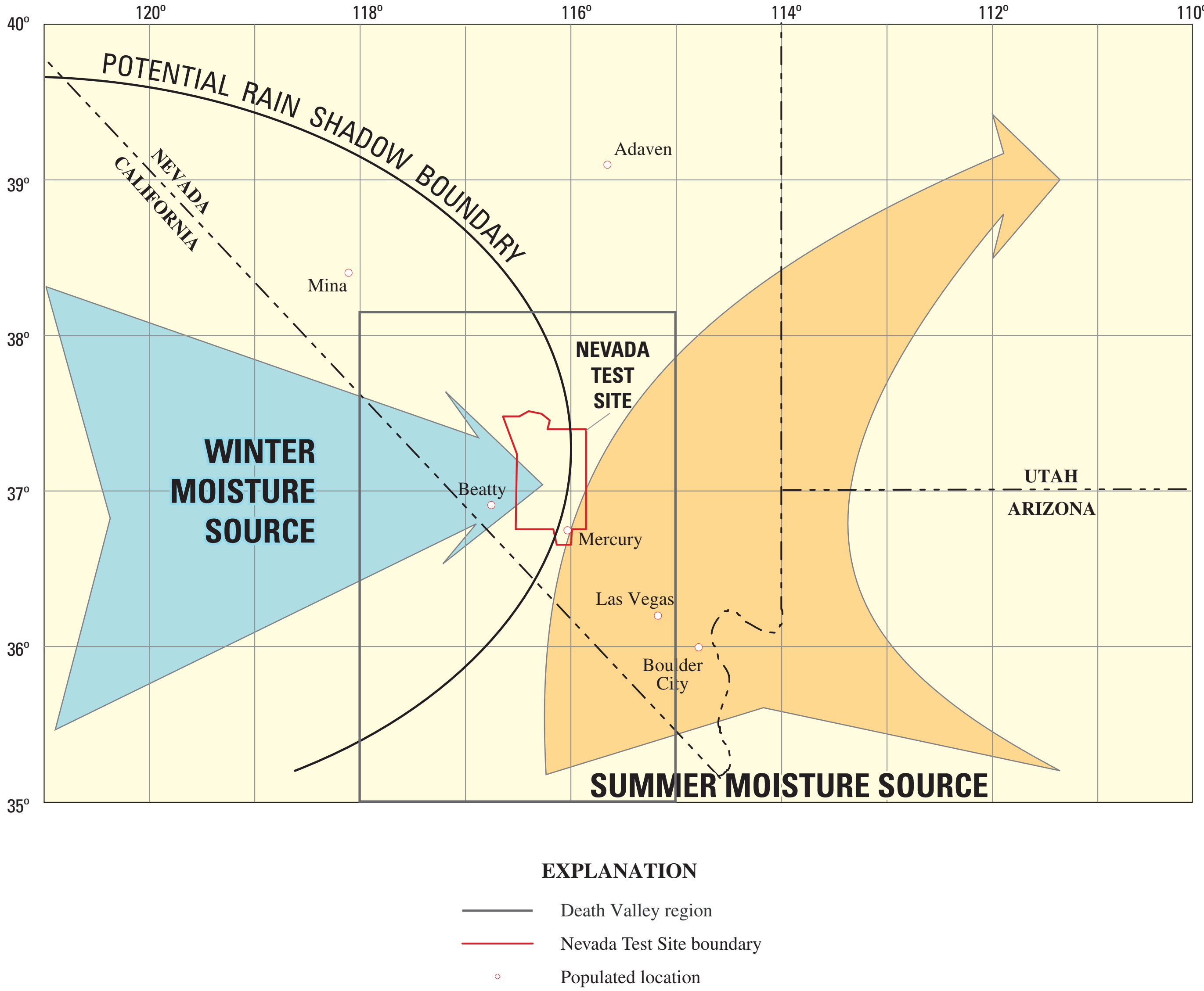


Figure A–4. Weather regimes of the Death Valley regional ground-water flow system region (Quiring, 1965).

Previous Work

Regional-scale ground-water flow models developed over the last 2 decades have provided new insights into ground-water flow in the DVRFS region. The NNSA/NSO and YMP have supported the construction of several such models to evaluate ground-water flow in the DVRFS. Successive models incorporated additional hydrogeologic complexity and computational sophistication in an effort to address increasingly complex water-resource issues in the region. Each of these studies attempted to model the complex hydrology and hydrogeologic framework, but the heterogeneity of the flow system was oversimplified because practical methods for representing the complex hydrogeologic framework were not available. With each model, investigators refined the understanding of the 3D nature of the DVRFS.

Early numerical ground-water modeling efforts were based on simplified conceptual models of the geology and hydrology known to exist in the region. Two- and three-dimensional ground-water flow models developed in the 1980’s contained considerable abstractions of the natural hydrogeologic conditions and depended on lumped system parameters (Waddell, 1982; Czarnecki and Waddell, 1984; Rice, 1984; Czarnecki, 1985; Sinton, 1987). Although these models were considered adequate for their intended purposes, the results of these investigations indicated that lumped-parameter representations do not necessarily adequately depict vertical ground-water flow components, subbasin ground-water flux, steep hydraulic gradients, and physical subbasin boundaries.

In contrast, the more complex ground-water flow models developed in recent investigations allow for the examination of the spatial and process complexities of the 3D hydrogeologic system (Prudic and others, 1995; IT Corporation, 1996a; D'Agnese and others, 1997; D'Agnese and others, 2002). These more geologically and hydrologically representative flow models usually require a 3D HFM to define the complexities of the hydrogeologic unit (HGU) geometry and structure.

Early Ground-Water Flow Models

Waddell (1982) used a 2D, finite-element model to simulate the ground-water system of the NTS. Data from two wells [USW G–2 (USGS Site ID 365322116273501) and USW WT–24 (USGS Site ID 365301116271301)] drilled after the completion of Waddell's model defined steep hydraulic gradients in the vicinity of Yucca Mountain and contradicted the results of the simulation. Waddell (1982) noted several model shortcomings:

1. The simulation was inaccurate in the eastern part of the Pahute Mesa area, possibly because of the limited amount of data available for the eastern and northeastern parts of the NTS.

2. Structural controls of ground-water flow were poorly represented.

3. Vertical flow components were ignored.

4. Estimation of transmissivity values from potentiometric data had large uncertainty.

Czarnecki and Waddell (1984) used a 2D, finite-element model to simulate and evaluate steady-state conditions in a subregional ground-water flow system in the Amargosa Desert. Parameter-estimation techniques using nonlinear regression were applied to head and flux data to estimate transmissivities within this flow system. Numerous simplifications were used to describe the flow system. As a result, the simulation did not adequately reproduce observed head values in areas where vertical-flow components and steep hydraulic gradients occurred. Sensitivity analyses indicated that rates of discharge and recharge provided important constraints on defining the ground-water flow system. Czarnecki (1985) improved on this model by adding a low-permeability zone that more accurately reproduced observed head values in the Amargosa Desert.

Rice (1984) developed a preliminary, 2D regional ground-water flow model of the NTS and vicinity using an approach similar to that used by Czarnecki and Waddell (1984). Although Rice's model contained detailed estimates of recharge and discharge, it ignored 3D heterogeneity. Because the model was developed primarily to assess flux, Rice assumed that using transmissivity values eliminated the need for detailed hydrogeologic framework characterization. Ultimately this 2D modeling approach prevented adequate simulation of vertical ground-water flow in Pahute Mesa and resulted in calibration difficulties. Rice (1984) recommended that a 3D model be constructed to correct this problem.

Sinton (1987) used a more sophisticated, quasi-3D, steady-state approach to characterize the regional ground-water flow system for the NTS. This model included two transmissive layers that represented the NTS flow system more accurately than did earlier models. The uppermost layer represented a shallow aquifer composed of volcanic rocks, basin-fill deposits, and lacustrine carbonate rocks. The lowermost layer represented a deep aquifer composed of carbonate and volcanic rocks. Horizontal flow was simulated within aquifer layers and vertical flow was simulated between layers and controlled using a vertical conductance term. The sensitivity analysis implied that the primary controls on ground-water flow were (1) the spatial distribution of low-permeability HGUs, (2) the distribution and magnitude of discharge and recharge locations, and (3) the rates of discharge and recharge. The analysis also revealed that small adjustments in recharge or discharge rates commonly produced substantial changes in the simulated magnitude and direction of ground-water flow. As a consequence, Sinton recommended that the following aspects of the flow system be investigated further:

1. The interaction between the lower carbonate aquifer and the overlying volcanic units,

2. The discharge rates at Ash Meadows, Death Valley, Alkali Flat, and other areas, and

3. The potential for recharge along Fortymile Wash and Fortymile Canyon.

Prudic and others (1995) developed a regional-scale numerical model of the carbonate-rock province of the Great Basin. This model simulated a conceptualized ground-water flow system containing a relatively shallow component in which water moved from mountain ranges to basin-fill deposits beneath adjacent valleys, as well as a deeper component in which water moved primarily through the carbonate rocks. This conceptual model is the basis of subsequent numerical models that describe regional ground-water flow in the DVRFS region. The calibrated numerical model indicated that:

1. The transmissivity values for basin-fill deposits and carbonate rocks in the upper layer are greater than those for other consolidated rocks.

2. The transmissivity values in the lower layer are greater in areas of regional springs.

3. Ground-water flow is relatively shallow, moving from recharge areas in mountain ranges to discharge areas in valleys.

4. Ground water discharges at deep regional springs or in areas with greater evapotranspiration rates.

5. Interbasin ground-water flow to larger regional springs occurs through carbonate rocks.

Recent Hydrogeologic Framework and Ground-Water Flow Models

The 3D ground-water flow models developed in recent investigations allow for the examination of the spatial and process complexities of the hydrogeologic system. These more geologically and hydrologically representative flow models are based on 3D HFMs to define the intricacies of the HGU geometry and structure. A digital HFM provides a computer-based description of the geometry and composition of the HGUs. Digital models defining the geometry and composition of the HGUs were constructed for several of the regional-scale ground-water flow models completed in the 1990's and early 2000's as part of the UGTA program at the NTS, and the YMP. These include the DOE/NV-UGTA model (IT Corporation, 1996b) for the UGTA Phase I work, the YMP/HRMP model (D'Agnese and others, 1997), and the merged YMP/HRMP and DOE/NV-UGTA framework model (Belcher and others, 2002). Figure A–5 presents the boundaries of each of these HFMs.

Underground Test Area (DOE/NV-UGTA) Model

The DOE/NV-UGTA HFM is a 3D geologic model that describes the hydrogeologic framework for the regional ground-water flow system around the NTS (IT Corporation, 1996b). The detailed hydrogeologic framework was required for the systematic estimation of hydrologic and radionuclide attenuation properties of the rocks through which any radionuclides related to nuclear weapons testing might migrate. The framework also was constructed to assess the regional distribution and thickness of aquifers and confining units as well as to determine the depth to the base of the ground-water flow system in a complex geologic terrane. The geologic model has constant grid-cell spacing of 2,000 m on a side and variable vertical thickness, extends from land surface to 7,600 m below sea level, and encompasses approximately 17,700 km^2. Twenty HGUs were modeled, including thrusted bedrock units. The DOE/NV-UGTA geologic model domain is centered on the NTS and extends from Death Valley to east of the East Pahranagat Range, and from the Black Mountains to north of Penoyer and the southern part of Railroad Valleys (fig. A–5). This model was developed on the basis of information from geologic reports, maps, measured stratigraphic sections, cross sections, well data, and geophysical interpretations. Fifty-four regional interpretive cross sections and approximately 700 lithologic well logs were used in constructing the HFM.

The DOE/NV-UGTA flow model is a regional 3D, steady-state flow model of the NTS and surrounding areas (IT Corporation, 1996a). This 20-layer model is designed to provide a basis for predicting the movement of contaminants from the underground nuclear weapons testing areas on a regional scale. The model is used for estimating the amount of water moving through the ground-water system, evaluating uncertainty in these predictions, and supplying boundary conditions for more detailed models of the underground testing areas.

The calibrated DOE/NV-UGTA model accurately simulates several observed hydrologic features on the NTS:

1. The steep hydraulic gradients between Emigrant Valley and Yucca Flat and north of the Yucca Mountain area,

2. The shape of the potentiometric surface in the western part of Yucca Flat,

3. A moderately flat hydraulic gradient beneath Timber Mountain, steepening to the north beneath Pahute Mesa,

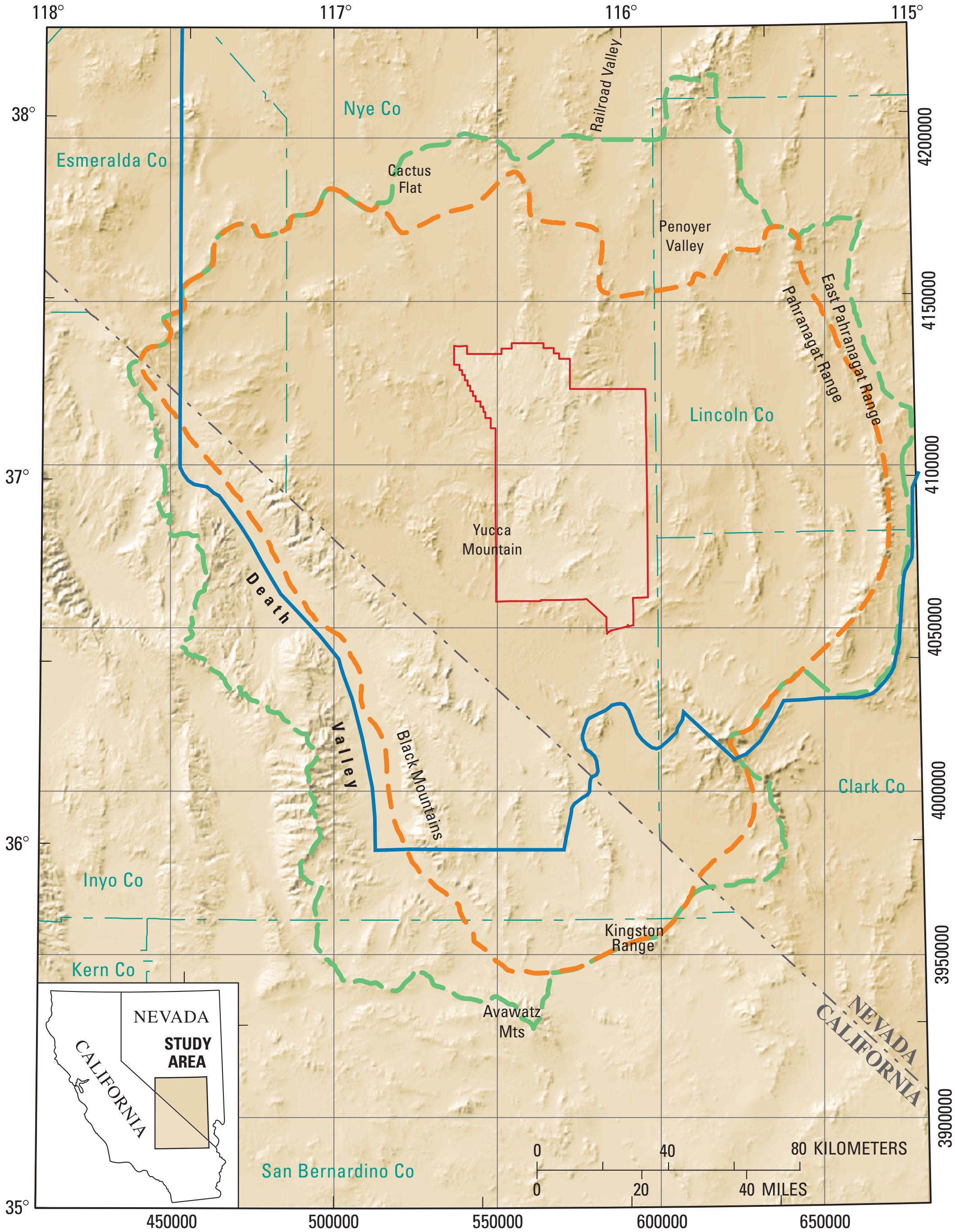
4. The trough in the potentiometric surface located in Area 20 on the western part of Pahute Mesa, and

5. Water budgets generally within expected ranges.

Yucca Mountain Project/Hydrologic Resource Management Program (YMP/HRMP) Model

The YMP/HRMP HFM is a 3D geologic model that describes the hydrogeologic framework for the regional ground-water flow system around Yucca Mountain (D'Agnese and others, 1997). The purpose of the model was to provide a description of the geometry, composition, and hydraulic properties that control regional ground-water flow for use in a regional steady-state ground-water flow model of the present-day system. The model grid is 1,500 m on a side with variable vertical thickness, extends from land surface to 10,000 m below sea level, and encompasses approximately 70,000 km^2. The model cells are attributed to define both the HGU and faulting conditions. Ten HGUs were modeled. The model domain is centered on Yucca Mountain and the NTS and extends from Death Valley to the East Pahranagat Range and from the Avawatz Mountains to Cactus Flat (fig. A–5). Development of the HFM was based on digital elevation models (DEM), geologic maps and sections, and lithologic well logs. Thirty-two regional cross sections, and approximately 700 lithologic well logs provided subsurface control for the HFM. Although thousands of faults have been mapped in the region, only 300 were used in constructing the HFM (D'Agnese and others, 1997).

The YMP/HRMP flow model is a 3D steady-state simulation of the present-day (pumped) DVRFS region (D'Agnese and others, 1997). The 3-layer model used a nonlinear least-squares regression technique to estimate aquifer-system variables (or parameters). The 3D simulation supported the analysis of interactions between the relatively shallow local and subregional flow paths and the deeper, dominant regional flow paths controlled by the regional carbonate-rock aquifer.



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11
Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

EXPLANATION

- Death Valley regional ground-water flow system hydrogeologic framework model boundary (Belcher and others, 2002)
- Yucca Mountain Project hydrogeologic framework ground-water flow model boundary (D'Agnese and others, 1997)
- Underground Test Area geologic model boundary (IT Corporation, 1996b)
- Nevada Test Site boundary

Figure A–5. Delineations of regional hydrogeologic framework models of the Death Valley regional ground-water flow system region.

Values of hydraulic head, spring flow, hydraulic conductivity, and water-budget components derived from the calibrated model were assessed for accuracy (D'Agnese and others, 1997). This assessment revealed that:

1. Simulated hydraulic heads matched observed conditions closely in nearly flat hydraulic-gradient areas and relatively well in steep hydraulic-gradient areas.

2. Simulated spring-flow volumes were generally less than observed values.

3. All estimated parameter values were within expected ranges.

4. Given the uncertainty, simulated water budgets were within the expected ranges for the flow system.

5. Weighted residuals were not entirely random, indicating some model error.

Death Valley Regional Ground-Water Flow System Prepumping Model

Belcher and others (2002) merged the two regional framework models constructed for YMP/HRMP (D'Agnese and others, 1997) and DOE/NV-UGTA (IT Corporation, 1996b) to produce a single, integrated HFM for use with a steady-state prepumping ground-water flow model (D'Agnese and others, 2002). Because of project-scope limitations, few interpretations were made where these two framework models disagree (mostly with respect to the HGUs defined for each HFM), and the hydrogeologic representation of the flow system is limited. During the merging process, the Cenozoic volcanic HGUs of the YMP/HRMP framework model were replaced by the Cenozoic volcanic HGUs of the DOE/NV-UGTA framework model. The more detailed Cenozoic basin-fill HGUs from the DOE/NV-UGTA framework model were used, augmented by the playa-deposits HGU from the YMP/HRMP model.

The DVRFS steady-state prepumping flow model (D'Agnese and others, 2002) simulated the flow system using a 3D steady-state model that incorporated a nonlinear least-squares regression technique to estimate aquifer-system parameters. This model had a vertical discretization that resulted in 15 model layers.The accuracy of the final calibrated DVRFS steady-state model was tested by comparing measured (observed) and expected values for heads, ground-water discharges, and parameter values, such as hydraulic conductivity, with simulated values (D'Agnese and others, 2002). The analysis resulted in the following observations:

1. A good fit between simulated and observed hydraulic heads generally was achieved in areas of low hydraulic gradients; a moderate fit to observed heads was achieved in the remainder of the nearly flat hydraulic-gradient areas; a poorer fit to observed heads was achieved in steep hydraulic-gradient areas; and the poorest fit to observed hydraulic heads was achieved in the vicinity of Indian Springs, the western part of Yucca Flat, and the southern part of the Bullfrog Hills. Most of the discrepancies can be attributed to (a) insufficient representation of the hydrogeology in the HFM, (b) misinterpretation of water levels, and (c) model error associated with grid-cell size.

2. Ground-water discharge residuals between simulated and observed values were generally interpreted to be random.

3. All resulting parameter values were within the range of expected values.

Overall evaluation of the model indicates that the steady-state prepumping DVRFS model reasonably represents the prepumping conditions for the DVRFS. Although the model is an improvement over previous representations of the flow system, important uncertainties and model errors remain. These uncertainties and errors include the quality of interpretation and representation of: (1) flow-model observations, (2) geometry and spatial variability of hydrogeologic materials and structures in the hydrogeologic-framework and ground-water flow models, and (3) physical framework and the hydrologic conditions in the flow model (D'Agnese and others, 2002). Furthermore, it is unclear whether the model of D'Agnese and others (2002) adequately simulates the DVRFS because the water table was simulated substantially below the uppermost layer of the model, and the flow system was simulated as confined (Richard K. Waddell, GeoTrans, written commun., 2002).

Summary

The hydrogeology, conceptual hydrologic model, and the hydrologic system inputs and outputs of the Death Valley regional ground-water flow system (DVRFS) region are used in this report to construct a hydrogeologic framework model and a transient numerical ground-water flow model. The ground-water flow model simulates transient conditions from 1913 through 1998 using the modular ground-water flow model, MODFLOW-2000, and a simulated steady-state head distribution representing prepumping conditions. Transient stresses imposed on the regional ground-water flow system include ground-water pumpage that occurred from 1913 through 1998, and flows from springs affected by pumping; simulated areal recharge was held constant at average annual values. The DVRFS region encompasses approximately 100,000 square kilometers in Nevada and California and is bounded by latitudes 35°00'N and 38°15'N and by longitudes 115°00'W and 118°00'W.

More than 20 years of ground-water flow modeling in the Death Valley region has produced a succession of models that are increasingly more realistic representations of the hydrogeologic framework and ground-water flow system. The current transient simulation, described in the following chapters, builds upon this substantial body of previous work and provides the most refined model of the DVRFS region to date.

References Cited

Beatley, J.C., 1976, Vascular plants of the Nevada Test Site and central-southern Nevada—Ecologic and geographic distributions: Technical Information Center, Office of Technical Information, Energy Research and Development Administration, Springfield, Va., 308 p.

Bedinger, M.S., Langer, W.H., and Reed, J.E., 1989, Ground-water hydrology, *in* Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste—Characterization of the Death Valley Region, Nevada and California: U.S. Geological Survey Professional Paper 1370–F, p. 28–35.

Belcher, W.R., Faunt, C.C., and D'Agnese, F.A., 2002, Three-dimensional hydrogeologic framework model for use with a steady-state numerical ground-water flow model of the Death Valley regional flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 01–4254, 87 p.

Benson, Lyman, and Darrow, R.A., 1981, Trees and shrubs of the southwestern deserts: Tucson, University of Arizona Press, 416 p.

Czarnecki, J.B., 1985, Simulated effects of increased recharge on the ground-water flow system of Yucca Mountain and vicinity, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 84–4344, 33 p.

Czarnecki, J.B., and Waddell, R.K., 1984, Finite-element simulation of ground-water flow in the vicinity of Yucca Mountain, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 84–4349, 38 p.

D'Agnese, F.A., Faunt, C.C., Turner, A.K., and Hill, M.C., 1997, Hydrogeologic evaluation and numerical simulation of the Death Valley regional ground-water flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 96–4300, 124 p.

D'Agnese, F.A., O'Brien, G.M., Faunt, C.C., Belcher, W.R., and San Juan, Carma, 2002, A three-dimensional numerical model of predevelopment conditions in the Death Valley regional ground-water flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 02–4102, 114 p. Accessed September 22, 2004, at *http://pubs.water.usgs.gov/wri024102/*.

Eakin, T.E., 1966, A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, no. 2, p. 251–271.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Company, Inc., 534 p.

French, R.H., 1983, A preliminary analysis of precipitation in southern Nevada: Water Resources Center, Desert Research Institute, DOE/NV/10162–10, 42 p.

Grose, T.L., and Smith, G.I., 1989, Geology, *in* Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste: U.S. Geological Survey Professional Paper 1370–F, p. 5–19.

Hales, J.R., Jr., 1972, Surges of maritime tropical air northward over the Gulf of California: Monthly Weather Review, v. 100, p. 298–306.

Hales, J.R., Jr., 1974, Southwestern United States summer monsoon source—Gulf of Mexico or Pacific Ocean?: Journal of Applied Meteorology, v. 13, p. 331–342.

Hanks, T.C., Winograd, I.J., Anderson, R.E., Reilly, T.E., and Weeks, E.P., 1999, Yucca Mountain as a radioactive-waste repository: U.S. Geological Survey Circular C1184, 19 p.

Harbaugh, J.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey's modular ground-water flow model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent States: U. S. Geological Survey Hydrologic Investigations Atlas HA–694–C, 2 sheets.

Harrill, J.R., and Prudic, D.E., 1998, Aquifer systems in the Great Basin region of Nevada, Utah, and adjacent States: U.S. Geological Survey Professional Paper 1409–A, 66 p.

Hill, M.C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient three-dimensional, ground-water flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91–484, 358 p.

Hunt, C.B. and Robinson, T.W., 1960, Possible interbasin circulation of ground water in the southern part of the Great Basin: U.S. Geological Survey Professional Paper 400–B, p. B273–274.

Hunt, C.B., Robinson, T.W., Bowles, W.A., and Washburn, A.L., 1966, Hydrologic basin, Death Valley, California: U.S. Geological Survey Professional Paper 494–B, 138 p.

IT Corporation, 1996a, Underground test area subproject, Phase I, Data analysis task, volume VI—Groundwater flow model data documentation package: Las Vegas, Nev., Report ITLV/10972–181 prepared for the U.S. Department of Energy, 8 volumes, various pagination.

IT Corporation, 1996b, Underground test area subproject, Phase I, Data analysis task, volume I—Geologic model data documentation package: Las Vegas, Nev., Report ITLV/10972–181 prepared for the U.S. Department of Energy, 8 volumes, various pagination.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada State Engineer, Water Resources Bulletin Number 8, 59 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p.

Peterson, F.F., 1981, Landforms of the Basin and Range province defined for soil survey: Nevada Agricultural Bulletin No. 28, Max C. Fleischmann College of Agriculture, University of Nevada, Reno, Nev., 53 p.

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent States: U.S. Geological Survey Professional Paper 1409–D, 102 p.

Quiring, R.F., 1965, Annual precipitation amount as a function of elevation in Nevada south of 38-1/2 degree latitude, Las Vegas, Nevada: U.S. Weather Bureau Research Statistics, 14 p.

Rice, W.A., 1984, Preliminary two-dimensional regional hydrologic model of the Nevada Test Site and vicinity: Albuquerque, N. Mex., Sandia National Laboratories Report SAND83–7466, 89 p.

Rush, F.E., 1968, Index of hydrographic areas in Nevada: Carson City, Nevada Department of Conservation and Water Resources, Water Resources Reconnaissance Series Report 54, 25 p.

Sinton, P.O., 1987, Three-dimensional, steady-state, finite-difference model of the ground-water flow system in the Death Valley ground-water basin, Nevada-California: Golden, Colorado School of Mines, Master's thesis, 145 p.

Waddell, R.K., 1982, Two-dimensional, steady-state model of ground-water flow, Nevada Test site and vicinity, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 84–4267, 72 p.