Hydrology

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Chapter D of

Death Valley Regional Groundwater Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model

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CHAPTER D. Hydrology

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Introduction

The hydrology of the Death Valley regional groundwater flow system (DVRFS), as in all flow systems, is influenced by geology and climate and varies with time. In general, groundwater moves through permeable zones under the influence of hydraulic gradients from areas of recharge to areas of discharge in the regional system (fig. D–1). The topography produces numerous local subsystems within the major flow system (Freeze and Cherry, 1979, p. 196). Water that enters the flow system in a recharge area may be discharged in the nearest topographic low, or it may be transmitted to a regional discharge area.

Groundwater flow in the DVRFS region is dominated by interbasin flow with several relatively shallow and local flow systems that are superimposed on deeper intermediate and regional flow systems (fig. D–1). The regional groundwater flow patterns do not coincide with local topographic basins. Regional groundwater flow generally follows the regional topographic gradient as water moves toward the lowest point in the region at Death Valley, Calif. (fig. D–2). Bedinger and Harrill (**plate 1** and Appendix 1, this volume) developed regional potentiometric-surface contours of the areas contributing groundwater flow to the DVRFS model domain to define the regional groundwater flow across the lateral boundary of the model. For conceptualization of the groundwater flow system and for the construction of a numerical flow model (D'Agnese and others, 1997), D'Agnese and others (1998) developed an approximation of the regional potentiometric surface. This surface depicted mounds, troughs, and depressions indicating areas of recharge and discharge that may be characteristic of a relatively shallow and local flow system (fig. D–2). Differences between the potentiometric surfaces of the deep regional system (**plate 1** and Appendix 1, this volume) and those in the shallower local systems depicted on D'Agnese and others (1998) are emphasized by areas of generally downward flow (recharge areas) to, and generally upward flow (discharge areas) from, the regional system (fig. D–2).

Hydrochemistry

The chemically and thermally dynamic nature of groundwater can be used to help define flow systems and evaluate the relative importance of groundwater sources and pathways using chemical, isotope, temperature, and hydraulic data for groundwater. For example, leakage from the carbonate-rock aquifer into overlying aquifers can be distinguished by differences in water quality along with differences in water temperature and hydraulic potential. Discharge temperatures for many modern springs commonly are higher than mean annual air temperature, indicating that the water has thermally equilibrated along deep flow paths. Cooler temperatures or lower altitude recharge are usually associated with shallower and shorter groundwater flow paths. Chemical and thermal heterogeneities are common in the DVRFS region due to fracture flow through contrasting lithologies, and these data were used, where possible, to help delineate the flow system.

Groundwater of the DVRFS region may be divided into hydrochemical categories that reflect equilibration with (1) tuffaceous rocks or tuffaceous basin-fill sediments (a sodium and potassium bicarbonate type); (2) primarily carbonate rocks or carbonate basin-fill sediments (a calcium and magnesium bicarbonate type); and (3) both kinds of rocks or sediments, or a mixing of different types of water (Schoff and Moore, 1964; Winograd and Thordarson, 1975). These categories define hydrochemical signatures for the water that can be used to identify sources and flow paths. In some areas water can reflect equilibration with playa deposits. Isotopic information from water or discharge deposits can provide substantial information on the hydrochemical signature of groundwater. For example, higher levels of strontium appear to be fairly common in water samples from the regional carbonate-rock aquifer (the associated carbonate rocks are relatively low in strontium), which indicates that more flow occurs through the fractured basement rocks (clastic and intrusive rocks, which are relatively high in strontium) than had been thought previously (Peterman and Stuckless, 1992a, b).

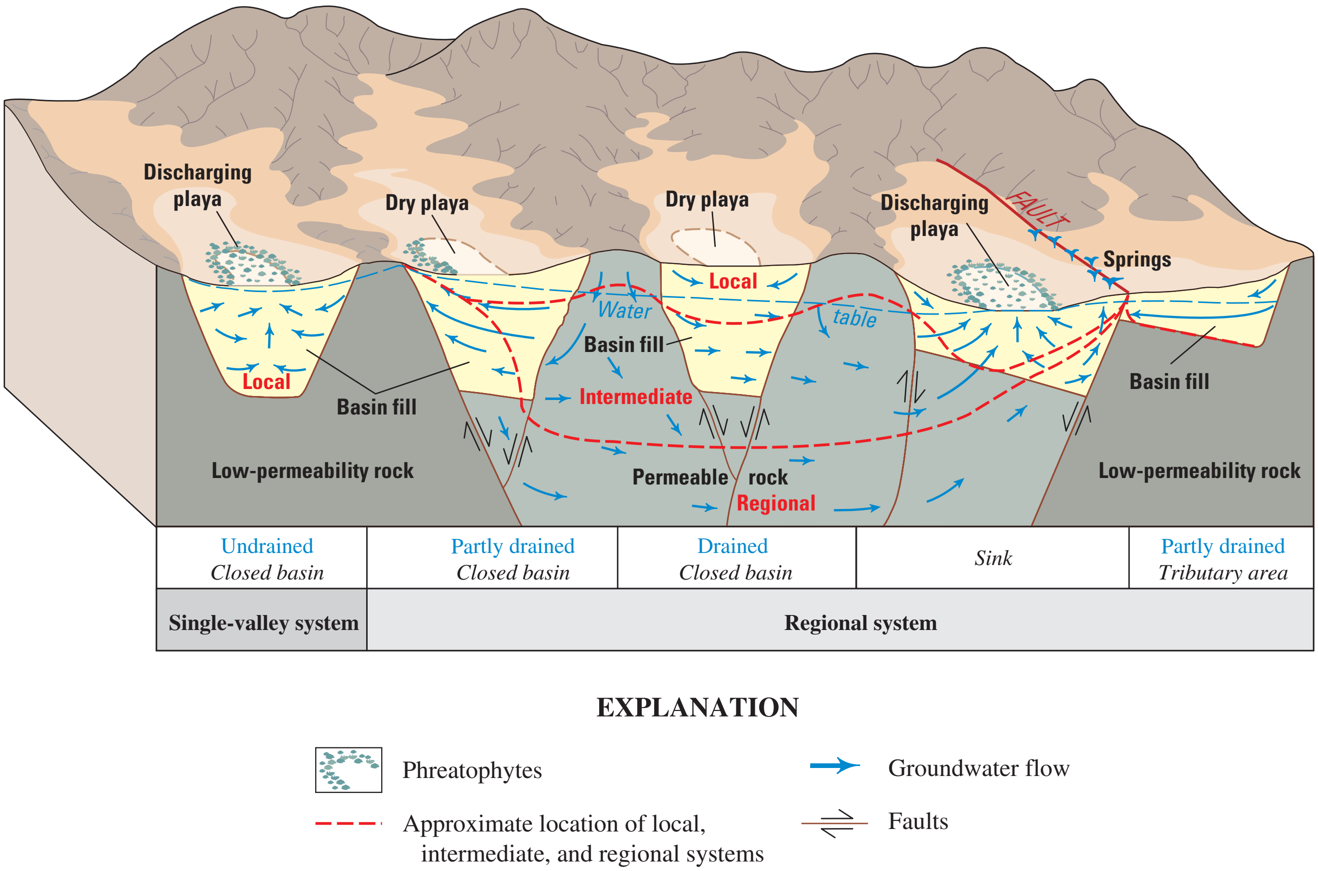


Figure D–1. Schematic block diagram of Death Valley and other basins illustrating the structural relations between mountain blocks, valleys, and groundwater flow (modified from Eakin and others, 1976).

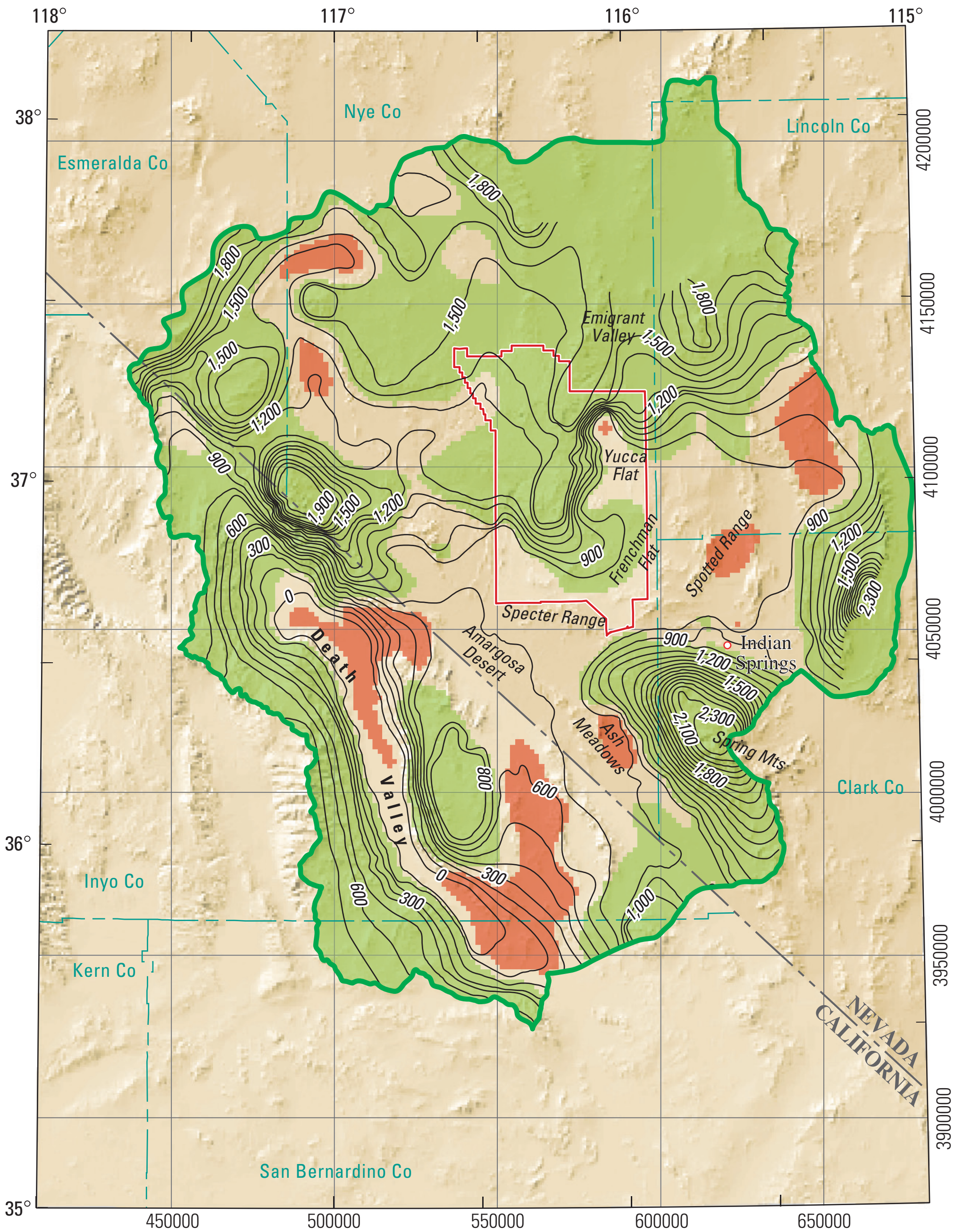
Groundwater Hydrology

Within the DVRFS region, groundwater flow is strongly influenced by the physical framework of the system, which is characterized by aquifers, confining units, and flow barriers. In order to simulate the regional flow system, the external and internal boundaries of the system must be identified.

Source and Movement of Groundwater

Current sources of groundwater flow in the DVRFS region are (1) recharge from precipitation in the mountains (usually winter storms) within the model domain, and (2) lateral flow into the model boundary, predominantly through the carbonate-rock aquifer. Most groundwater recharge results from infiltration of precipitation and runoff on the mountain ranges (Bedinger and others, 1989) (fig. D–3). Water may infiltrate from melting snowpack in the mountains primarily on volcanic or carbonate rocks or adjacent to the mountains from streams flowing over alluvium (fans and channels) (Harrill and Prudic, 1998). Lateral groundwater flow across the model boundary is governed in part by regional hydraulic gradients in the DVRFS region.

Groundwater discharge in the DVRFS region is from (1) seeps and spring flow from the regional carbonate-rock aquifer and local systems; (2) evapotranspiration (ET); (3) pumpage for irrigation, mining, public supply, commercial, and domestic uses; and (4) subsurface flow out of the model boundary (fig. D–3 and **plate 1**). Most groundwater discharge today originates as spring or seep flow caused by variations in permeability created by geologic structures and varying lithologies (Winograd and Thordarson, 1975; Chapter B, this volume; fig. D–1). In particular, many of the regional (larger volume and higher temperature) springs occur along major faults (figs. D–1 and D–3). Most spring discharge is ultimately consumed by ET. Major discharge areas primarily occur in the lower part of intermontane valleys where the potentiometric surface is near or above land surface. Discharge also occurs as pumping for irrigation, mining, public supply, commercial, and domestic uses (Bedinger and others, 1989; Moreo and others, 2003; Chapter C, this volume) (fig. D–3). Lateral flow into the model domain, predominantly through the carbonate-rock aquifer, is small compared to the internal discharge (fig. D–3; Appendix 2, this volume).



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

0 40 80 KILOMETERS
0 20 40 MILES

EXPLANATION

Generalized area of potential discharge from regional system

Generalized area of potential recharge to regional system

Areas are delineated on the basis of differences between potentiometric surfaces in the deep regional flow system (Plate 1 and Appendix 1, this volume) and those in shallower, local systems (D'Agnese and others, 1998)

300 **Potentiometric-surface contour—**In meters above sea level. Contour interval 100 meters (D'Agnese and others, 1998)

Death Valley regional groundwater flow system model boundary

Nevada Test Site boundary

Populated place

Figure D–2. Generalized areas of potential recharge and discharge based on potentiometric surfaces for the Death Valley regional groundwater flow system model.

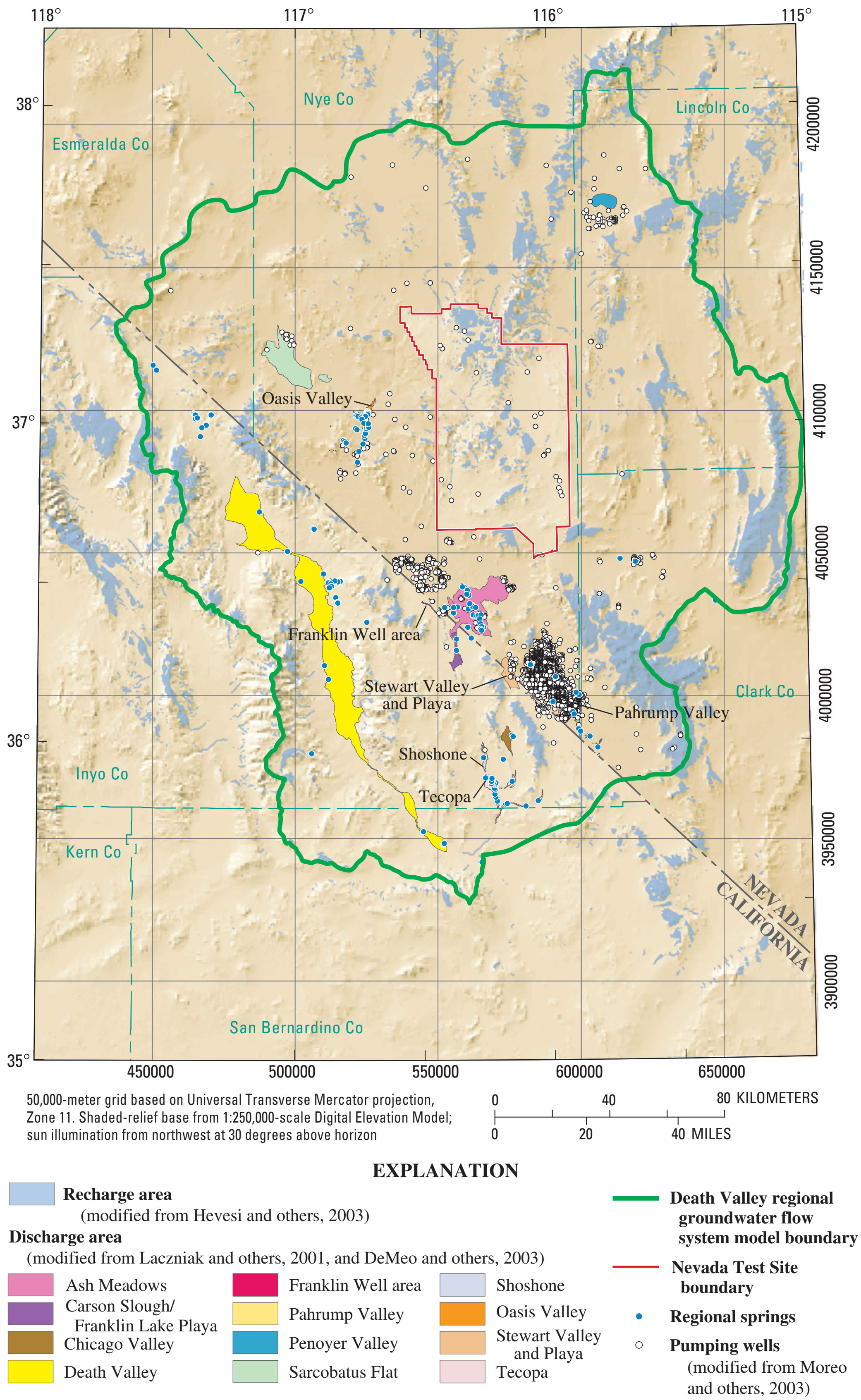


Figure D–3. Generalized areas of recharge and discharge, and location of regional springs and pumping wells in the Death Valley regional groundwater flow system region.

Regional Aquifers, Flow Barriers, and Confining Units

Hydraulic compartmentalization may occur throughout the DVRFS region owing to the complex hydrogeologic framework. Groundwater flows through a diverse assemblage of rocks and sediments in the region, and geologic structures exert significant control on groundwater movement as well (Chapter B, this volume).

Hydrogeologic units (HGUs) that are important to the hydrology of the DVRFS region include Cenozoic basin-fill units, Cenozoic volcanic-rock units of the southwestern Nevada volcanic field, the carbonate-rock aquifer, and confining units present at the water table (fig. D–4). Three types of aquifers exist in the region: basin-fill, volcanic-rock, and carbonate-rock aquifers (Chapter B, this volume). Some groundwater basins are part of multibasin flow systems connected by surface-water streams or by flow through the basin-fill sediments or permeable bedrock, and others are topographically and hydraulically isolated by low-permeability bedrock (figs. D–1 and D–4).

Juxtaposition of thick, low-permeability siliciclastic-rock strata and rocks forming aquifers by folding or faulting commonly forms barriers to groundwater flow (Chapter B, this volume). Although the siliciclastic rocks are subjected to the same deformational history as the carbonate rocks, the siliciclastic rocks are generally relatively impermeable because of their low susceptibility to solution and their lack of significant secondary permeability. Most of the siliciclastic rocks, when deformed, will break into fragments that reconsolidate into impermeable rock (quartzites) or will yield ductilely (shale) and, in either case, will not result in significant openings through which water can flow. In general, crystalline rocks have low permeability; however, where fractured, crystalline rocks may have significant permeability (Winograd and Thordarson, 1975).

In the DVRFS region, the relative permeability of faulted rock may vary either directly as the result of the fault orientation with respect to the present-day stress field or indirectly as zones of fracturing adjacent to the fault. The present-day stress field in the DVRFS region tends to enhance flow along northeast-southwest-trending features while decreasing the permeability along features oriented northwest-southeast (Carr, 1984; Faunt, 1997). Despite their orientation to the stress field, faults with low-permeability gouge may be barriers to groundwater flow (Winograd and Thordarson, 1968).

Flow-System Model Boundaries

The DVRFS model domain is contained within the DVRFS and can be defined by a series of boundaries. For modeling purposes, a groundwater flow system is a set of three-dimensional (3D) pathways through the subsurface rocks and sediments by which groundwater moves from recharge areas to discharge areas. Below the water table, the saturated volume of rock is bounded on all sides by a boundary surface (Franke and others, 1987). For the flow-system model, this boundary surface is represented by the upper, lower, and lateral extents of the model.

The upper boundary of the DVRFS model is the water table. Under natural (prepumping) conditions, water moves across this boundary as recharge or as discharge. When stressed (from climate change or pumping), the upper boundary may fluctuate with changes in recharge and discharge.

The lower boundary of the DVRFS model is the depth at which groundwater flow is dominantly horizontal or parallel to the boundary. Near the lower boundary, permeabilities are so low that flow near this boundary does not substantially affect regional flow. The depth of this boundary can vary and generally corresponds to the upper surface of low-permeability basement rocks.

The lateral boundary of the DVRFS model is a combination of no-flow boundaries resulting from physical barriers or hydraulic separation of flow regimes (groundwater divides and[or]) regional flow lines) and arbitrary lateral-flow (throughflow) boundaries where water is allowed to flow across the model boundary. When the system is at steady state, no-flow conditions exist where groundwater movement across the boundary is impeded by physical barriers, which results in flow paths parallel to the boundary, or where groundwater flow paths diverge, which results from groundwater divides. Under transient-state conditions, the location of flow paths and groundwater divides may shift if hydraulic-head changes occur. An estimated regional potentiometric-surface map was developed for the DVRFS region to delineate areas outside the model domain that contribute inflow to or receive outflow from the DVRFS across the model boundary (Appendixes 1 and 2, this volume; **plate 1**).

Flow-System Subregions

Groundwater flow in the DVRFS model domain is described simply in terms of the northern, central, and southern Death Valley subregions (fig. D–5) of D'Agnese and others (1997, p. 62–67). The subregions are further subdivided into groundwater sections, with the sections in the central Death Valley region grouped into groundwater basins (table D–1). These subregions, basins, and sections are used for descriptive purposes only, and the boundaries do not define independent flow systems. The subregions, basins, and sections are delineated primarily on (1) location of recharge areas; (2) regional hydraulic gradients; (3) distribution of aquifers, structures, and confining units that affect flow; (4) location of major discharge areas; and (5) hydrochemical composition of the groundwater. Flow directions across the model boundary, as indicated in figure D–5, are based on the lateral flow estimates provided in Appendix 2.

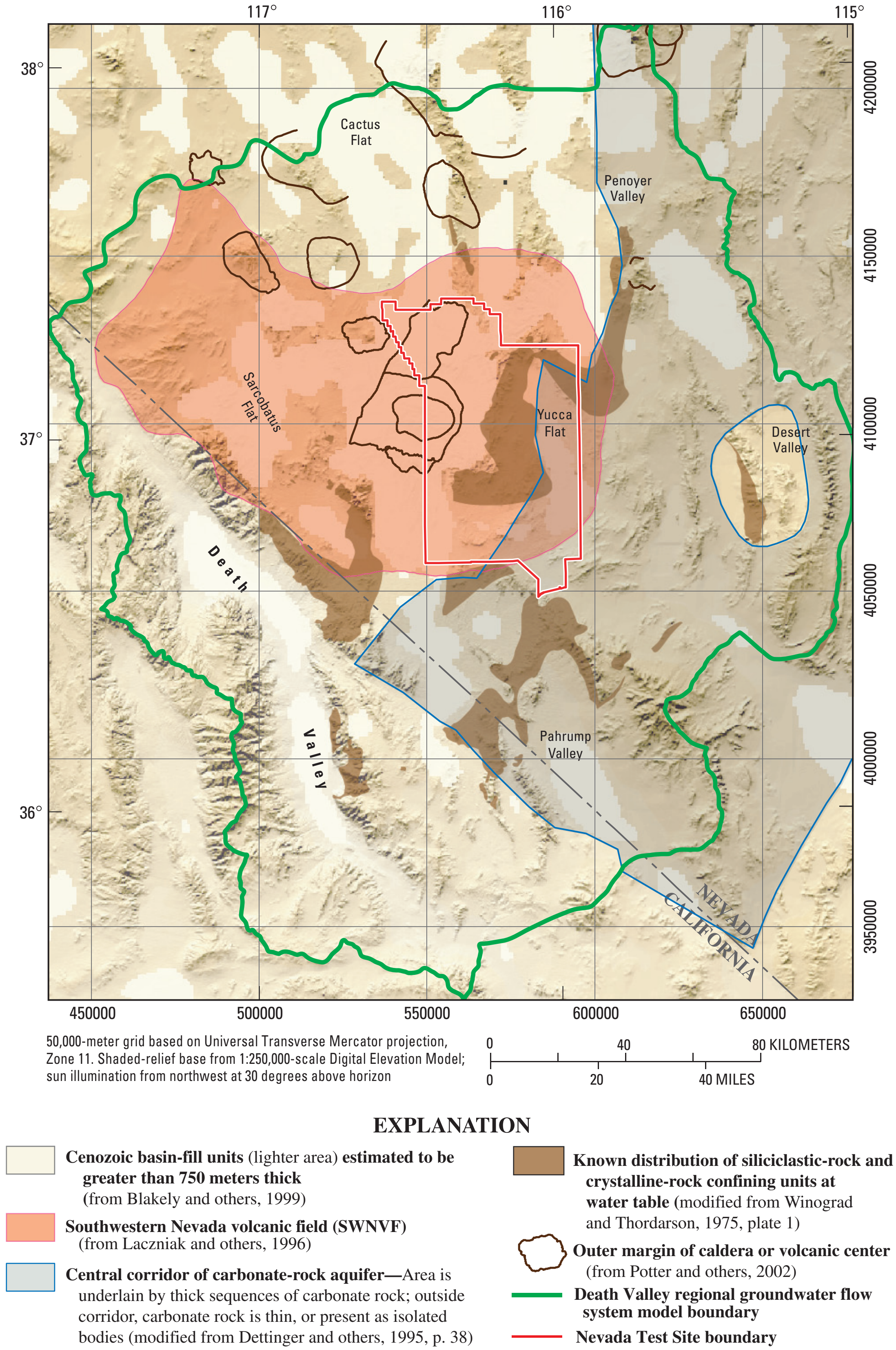


Figure D–4. Generalized distribution of deep Cenozoic basins, southwestern Nevada volcanic field, regional carbonate-rock aquifer, and confining units at the water table for the Death Valley regional groundwater flow system region.

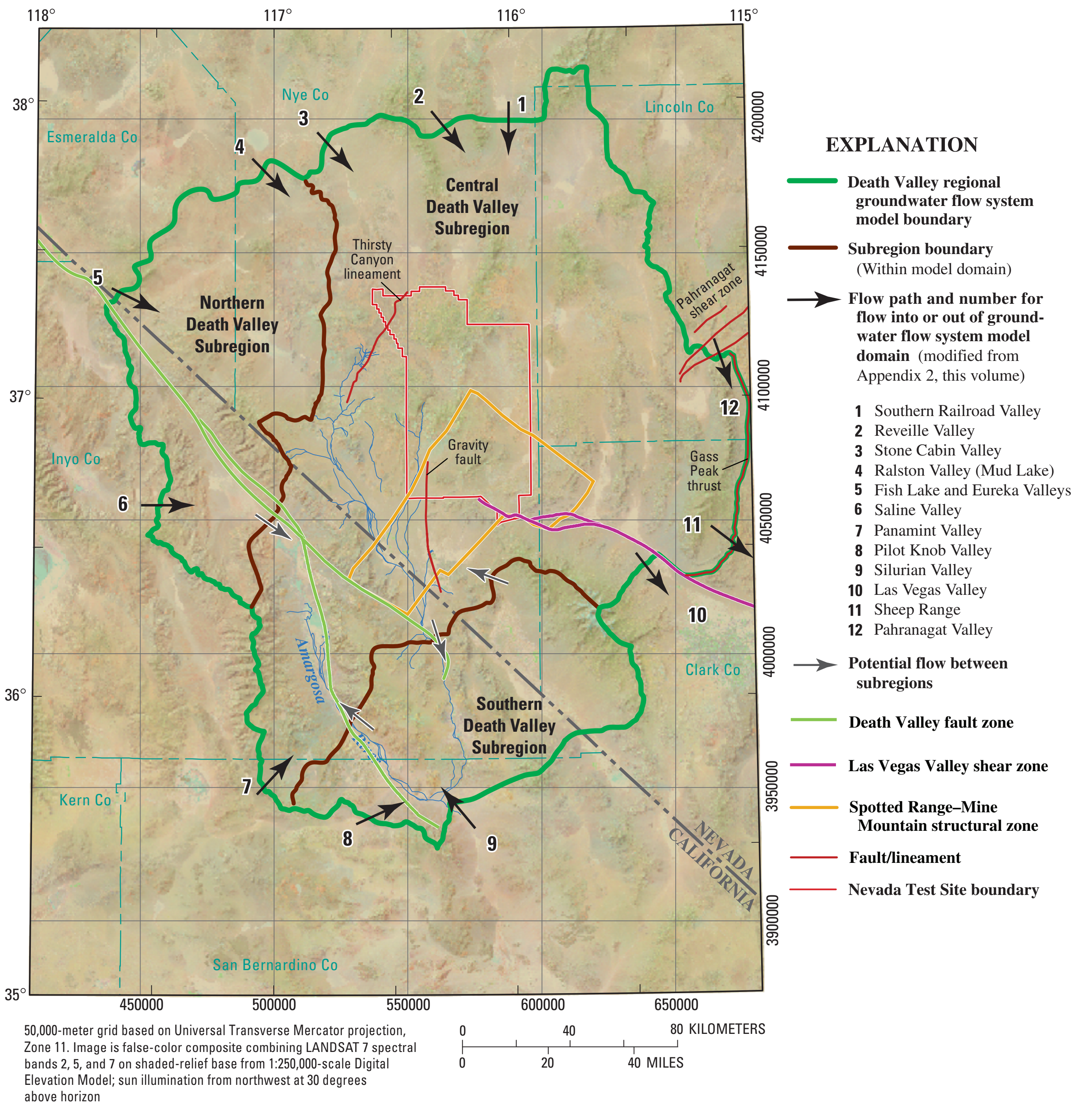


Figure D–5. Subregions and associated flow paths of the Death Valley regional groundwater flow system region.

Northern Death Valley Subregion

Groundwater in the northern Death Valley subregion is derived from precipitation on the Montezuma and Panamint Ranges, Slate Ridge, and the Palmetto, Gold, and Stonewall Mountains (fig. D–6). Groundwater also may be entering the subregion across the DVRFS model boundary from Eureka Valley and the southern part of Saline Valley and possibly across the northern part of the Panamint Range (Appendix 2, this volume). Much of the groundwater flow is controlled by northeast-southwest-trending structural zones (Carr, 1984; Chapter B, this volume). Deep regional flow is unlikely because the relatively low-permeability, shallow, intrusive-rock confining unit (ICU), the lower clastic-rock confining unit (LCCU), and the crystalline-rock confining unit (XCU) underlie most of the subregion. Extensive outcrops of the lower carbonate-rock aquifer (LCA) occur in the Grapevine and Cottonwood Mountains in the southern part of the subregion. The LCA has been interpreted to exist in the subsurface in the southern part of the subregion (Grose, 1983; Sweetkind

Table D–1. Divisions of the Death Valley regional groundwater flow system.

Northern Death Valley Subregion
Lida-Stonewall section
Sarcobatus Flat section
Grapevine Canyon–Mesquite Flat section
Oriental Wash section
Central Death Valley Subregion
Pahute Mesa–Oasis Valley groundwater basin
Southern Railroad Valley–Penoyer Valley section
Kawich Valley section
Oasis Valley section
Ash Meadows groundwater basin
Pahranagat section
Tikaboo Valley section
Indian Springs section
Emigrant Valley section
Yucca–Frenchman Flat section
Specter Range section
Alkali Flat–Furnace Creek groundwater basin
Fortymile Canyon section
Amargosa River section
Crater Flat section
Funeral Mountains section
Southern Death Valley Subregion
Pahrump Valley section
Shoshone–Tecopa section
California Valley section
Ibex Hills section

and others, 2001), including the southern part of Sarcobatus Flat and in the vicinity of Grapevine Springs in the northern part of Death Valley. Pumpage in the northern Death Valley subregion has been negligible, and the change in the volume of groundwater storage relative to the total amount in storage is negligible (Moreo and others, 2003). The subregion can be divided into four sections: Lida-Stonewall, Sarcobatus Flat, Grapevine Canyon–Mesquite Flat, and Oriental Wash.

The Lida-Stonewall section (section A, fig. D–6) potentially receives recharge by throughflow from Ralston Valley and precipitation on areas along the northern boundary of the subregion. The dominant regional flow path is to the south. Field observation and analysis of satellite imagery reveal that the playas at Stonewall Flat and near Lida Junction have very little phreatophytic vegetation, indicating that the small amounts of ET in these areas are probably from local surface water that infiltrates intermittently. Discharge from the section occurs as throughflow to Sarcobatus Flat and Death Valley.

Groundwater in the Sarcobatus Flat section (section B, fig. D–6) may originate on the western part of Pahute Mesa (D'Agnese and others, 1997) and flows southwest as throughflow from the central Death Valley subregion by way of Cactus and Gold Flats. Throughflow from the Lida-Stonewall section also may contribute flow to the section. Precipitation on the Grapevine Mountains may contribute recharge in the western part of Sarcobatus Flat, but is not sufficient to maintain the discharge at Sarcobatus Flat. Other potential sources of recharge for this area are Pahute Mesa and the Kawich Range to the east. Groundwater may flow to the southeast along or parallel to buried structures (Grauch and others, 1999) discharging by ET at areas on or adjacent to the playas of Coyote Hole or Sarcobatus Flat. Recent studies indicate that discharge at Sarcobatus Flat is much greater than previously thought (Laczniak and others, 2001). As a result, throughflow from Ralston Valley and from the central Death Valley subregion may be much greater than described by D'Agnese and others (1997). In addition, uncertainty exists about the potential for groundwater flow through the Bullfrog Hills to Amargosa Desert.

Groundwater in the Grapevine Canyon–Mesquite Flat section (section C, fig. D–6) originates as throughflow from the northeast past Sarcobatus Flat (D'Agnese and others, 1997). Additional groundwater may enter the flow system from Saline Valley. A small amount of recharge may result from precipitation on the Grapevine Mountains. The Grapevine Canyon–Mesquite Flat section contains a major discharge area that includes Grapevine and Staininger Springs. These high-discharge springs are aligned with northeast-oriented regional structural features (Carr, 1984) and their waters have chemical characteristics indicative of an origin from rocks in the eastern part of the DVRFS region (Steinkampf and Werrell, 2001). In addition, numerous seeps and low-discharge springs in and along the flanks of the Grapevine Mountains reflect structural controls of flow on local recharge and the chemistries of these sources (Steinkampf and Werrell, 2001). Groundwater that does not discharge at these springs and seeps continues past this discharge area to flow through Death Valley to discharge at Mesquite Flat or farther down the valley. Potential inflow from Saline Valley may discharge at Mesquite Flat or continue through Death Valley.

Some groundwater in the Oriental Wash section (fig. D–6) is from locally derived recharge on the predominantly granitic mountains to the north. In addition, groundwater may enter the system as throughflow from Eureka and Saline Valleys. Groundwater flow is apparently directed toward a small-volume and low-temperature spring area at Sand Spring in the northern part of Death Valley along the axis of Oriental Wash. This spring area appears to be associated with a northeast-southwest-trending structural zone (Carr, 1984), and the discharge occurs along the northern terminus of the Death Valley fault zone. Some groundwater moving along this flow path may bypass Sand Spring and flow through Death Valley toward Mesquite Flat.

Central Death Valley Subregion

In the central Death Valley subregion, the dominant flow paths have been interpreted to be associated with major regional or intermediate discharge areas and have been grouped into three groundwater basins based on the major discharge areas (fig. D–7): Pahute Mesa–Oasis Valley basin, Ash Meadows basin, and Alkali Flat–Furnace Creek basin (Waddell, 1982; D'Agnese and others, 1997, 2002).

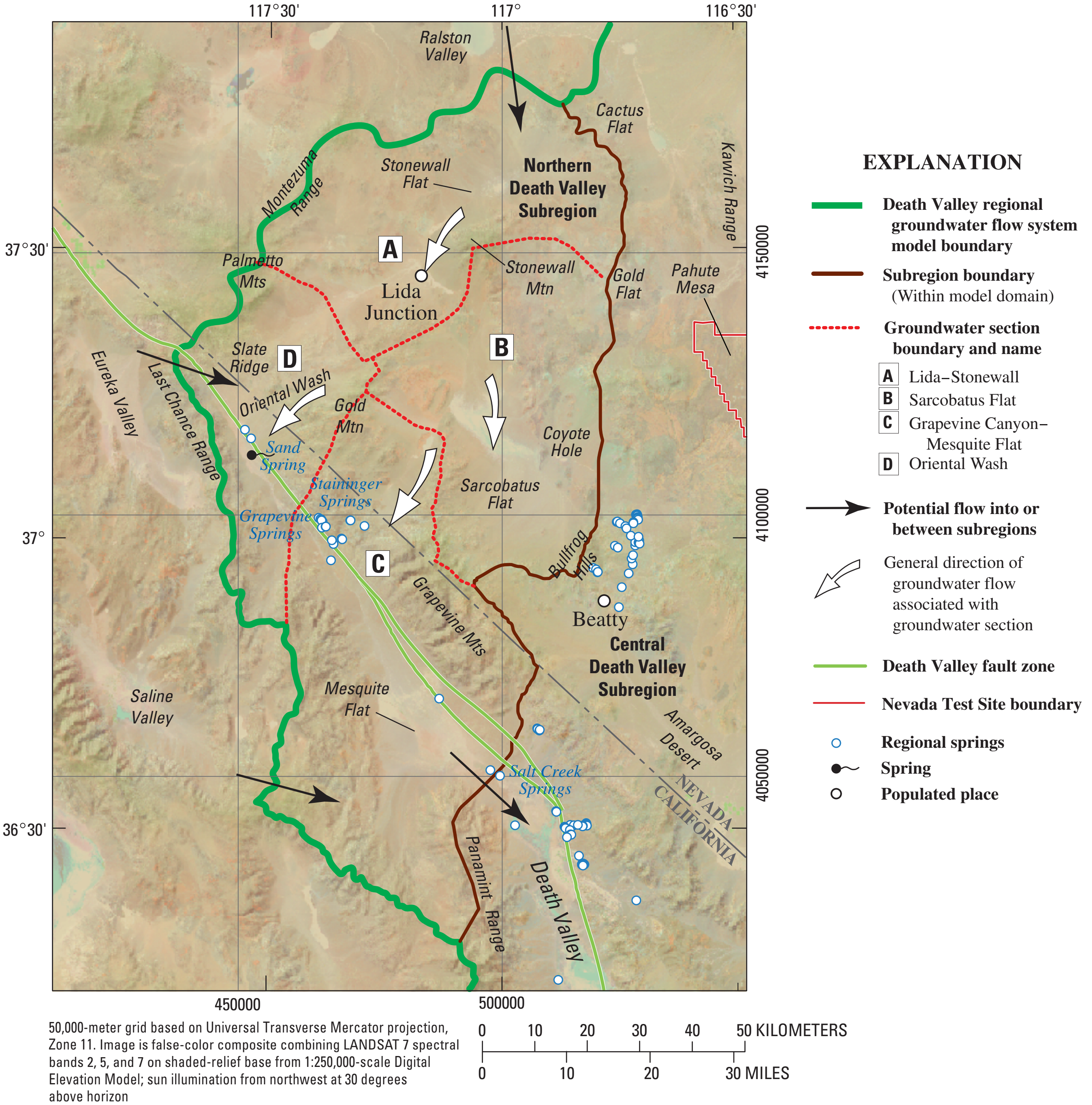


Figure D–6. Northern Death Valley subregion of the Death Valley regional groundwater flow system showing groundwater sections and flow directions.

Pahute Mesa–Oasis Valley Basin

The Pahute Mesa–Oasis Valley groundwater basin is the smallest and northernmost of the three basins and its extent is not well defined (fig. D–7). Groundwater is derived primarily from recharge in Pahute Mesa and the Kawich, Cactus, and Belted Ranges (D'Agnese and others, 1997). Additional recharge from within the basin may occur at Black and Quartz Mountains. Throughflow into the Pahute Mesa–Oasis Valley basin may occur from the southern part of Railroad, Reveille, and Stone Cabin Valleys (Appendix 2, this volume).

At Oasis Valley, groundwater is diverted upward by the confining units along faults to discharge by ET and spring flow at and along the flood plain of the Amargosa River and tributary drainages (fig. D–5) (White, 1979; Laczniak and others, 1996). Mass-balance calculations indicate that about one-half the water that flows to Oasis Valley discharges through ET

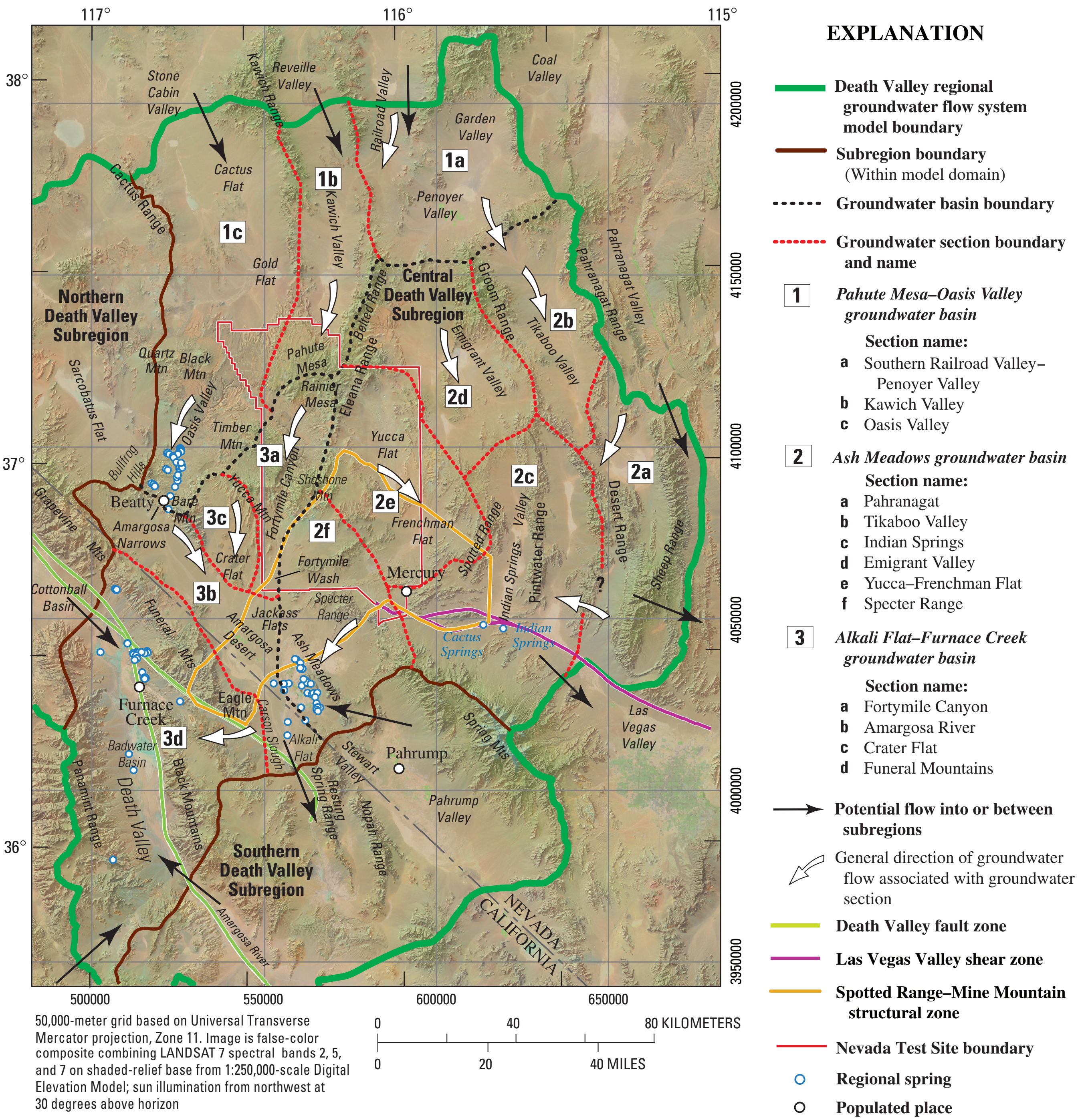


Figure D–7. Central Death Valley subregion of the Death Valley regional groundwater flow system showing groundwater basins, sections, and flow directions.

(White, 1979). Groundwater that does not discharge within Oasis Valley flows through a veneer of alluvium or the low-permeability basement rocks at Amargosa Narrows south of Beatty, Nev. (fig. D–7), and into the Alkali Flat–Furnace Creek basin (Waddell, 1982; Laczniak and others, 1996).

Some groundwater may not reach Oasis Valley and may flow around the northern part of Bare Mountain toward Crater Flat (fig. D–7). Likewise, some groundwater in the northwestern part of the section (parts of Cactus and Gold Flats) may flow toward the eastern part of Sarcobatus Flat. Based on general flow patterns, the Pahute Mesa–Oasis Valley basin may be divided into three sections: southern Railroad Valley–Penoyer Valley, Kawich Valley, and Oasis Valley.

Groundwater in the southern Railroad Valley–Penoyer Valley section originates either as recharge on the flanking mountains or as throughflow from the north (fig. D–7)

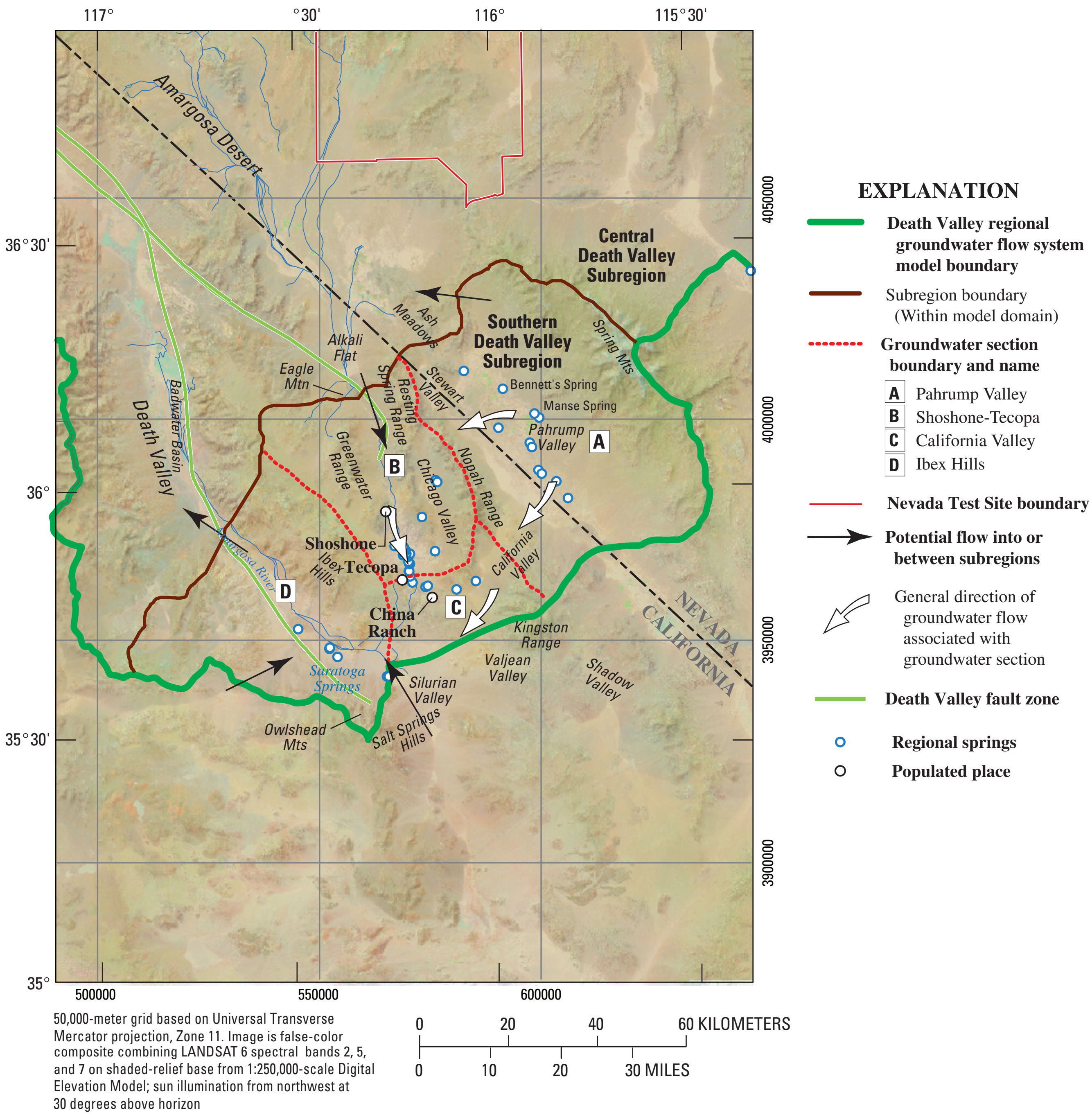


Figure D–8. Southern Death Valley subregion of the Death Valley regional groundwater flow system showing groundwater sections and flow directions.

(D'Agnese and others, 1997; Appendix 2, this volume). Groundwater in the section flows dominantly south and southwest toward Kawich Valley and southeast toward Penoyer and Emigrant Valleys. The section has little internal discharge and most, if not all, of the water leaves the system as throughflow. Penoyer Valley traditionally has been characterized as part of the White River groundwater flow system. Some studies indicate that it is possible that the valley is connected to the DVRFS (IT Corporation, 1996). A small discharge area occurs at the playa in the southern part of Penoyer Valley. Water that is not discharged there may continue to flow south into Emigrant and Tikaboo Valleys.

Groundwater in the Kawich Valley section originates mainly as throughflow from the southern Railroad Valley section and as recharge on the Kawich Range and Pahute and Rainier Mesas (fig. D–7). On Pahute and Rainier Mesas, water percolates down and commonly contacts low-permeability volcanic rocks, forming perched and semiperched water that can be elevated several hundred meters above the regional water table. From the recharge areas, groundwater in the Kawich Valley section flows toward a trough in the potentiometric surface beneath the western part of Pahute Mesa (figs. D–2 and D–7) (Waddell and others, 1984). The Thirsty Canyon lineament (fig. D–5) may act as a limited-flow barrier, created by caldera-boundary faults juxtaposing low-permeability rocks on the west and more permeable rocks to the east, diverting westward-moving water to the south (Blankennagel and Weir, 1973, p. 24). The hydraulic gradient across the barrier indicates some eastward flow. The barrier concept is supported by distinct differences in the major anion chemistry of groundwater samples collected on either side of the feature (Laczniak and others, 1996). This section has little internal discharge. Groundwater leaving the southern margins of Pahute Mesa flows southwestward in Oasis Valley toward the Amargosa River and south through Fortymile Canyon, ultimately discharging at Oasis Valley, Alkali Flat, and(or) Death Valley.

The Oasis Valley section contains the major discharge area for the basin. The section receives subsurface inflow from the Kawich Valley section, by way of Pahute Mesa, and Gold Flat to the north is the largest source of groundwater to the Oasis Valley section (fig. D–7) (Laczniak and others, 1996; White, 1979). The location and nature of the boundary separating the Oasis Valley section from the Alkali Flat–Furnace Creek basin is not well understood, and it is uncertain how much of the water discharging at Oasis Valley actually passes through rocks beneath Pahute Mesa (Laczniak and others, 1996).

Water is withdrawn for irrigation, domestic, and public supply in upper Oasis Valley. Pumping occurred periodically since the 1950s on the Pahute Mesa–Oasis Valley basin part of the Nevada Test Site for water supplies and long- and short-term aquifer tests to help characterize the flow system. Most of this development has been small in scale and likely has had little long-term effect on the system. Similarly, the relatively small amount of pumpage in the area of Penoyer Valley for irrigation likely has had little long-term effect (Moreo and others, 2003).

Ash Meadows Basin

The Ash Meadows basin is the largest basin in the central Death Valley subregion (fig. D–7) (Waddell, 1982). Much of the groundwater in this basin is derived from recharge on the Spring Mountains and the Sheep, Pahranagat, and Belted Ranges. Recharge also may occur within the basin on the Spotted, Pintwater, and Desert Ranges (Laczniak and others, 1996). The Ash Meadows basin is subdivided into six sections: Pahranagat, Tikaboo Valley, Indian Springs, Emigrant Valley, Yucca–Frenchman Flat, and Specter Range.

The Ash Meadows discharge area (fig. D–7) represents the terminus of the Ash Meadows basin. Water entering Ash Meadows encounters a northwest-southeast-trending fault that juxtaposes fine-grained basin-fill sediments and the more permeable carbonate-rock aquifer (Dudley and Larson, 1976, p. 9–10). The discharge at Ash Meadows occurs at approximately 30 springs along a 16-kilometer (km) long spring line that generally coincides with the trace of the buried fault. All the major springs emerge from circular pools, are relatively warm, and discharged at nearly constant rates from 1953 until agricultural development began in the area in 1969 (Dettinger and others, 1995, p. 79). Most of the spring discharge at Ash Meadows may reinfiltrate and recharge the basin-fill aquifers, much of this discharging as ET from the alluvium along the Amargosa River, Carson Slough, and Alkali Flat (Czarnecki and Waddell, 1984; Czarnecki, 1997).

Groundwater is pumped from wells scattered throughout the Ash Meadows basin. Wells near Ash Meadows tap the basin-fill aquifers adjacent to the carbonate-rock aquifer. Wells on the NTS within the basin are used to supply about 50 percent of the water demand at the NTS (Laczniak and others, 1996). Pumping from basin-fill aquifers around Devils Hole, a collapse feature in the carbonate rock supporting an endemic species of desert pupfish (*Cyprinidon diabolis*) (see fig. A–1), caused water-level declines observed in Devils Hole and the decrease or temporary cessation of flow from several major springs issuing from the carbonate aquifer. After pumping ceased, water levels and spring flow gradually recovered. The effect of pumping on individual springs differed, indicating that a variable degree of hydraulic connection exists between the basin-fill and carbonate-rock aquifers (Dettinger and others, 1995, p. 80).

Previous conceptual models of the Ash Meadows basin indicate significant amounts of flow from Pahranagat Valley to Ash Meadows. Evaluations of hydrochemical data, however, indicate that the volume of this inflow could be negligible (J.M. Thomas and William Sicke, Desert Research Institute, Reno, Nev., written commun., 2003). Analysis of calcite veins precipitated at Devils Hole (Winograd and others, 1992) also indicates that most, if not all, of the groundwater in Ash Meadows originates from the Spring Mountains.

Groundwater that bypasses the springs at Ash Meadows may continue as throughflow to Furnace Creek (fig. D–7) or may recharge the basin-fill sediments and join other groundwater in the basin-fill sediments to flow southward toward Alkali Flat, where it either discharges or continues south to the southern Death Valley subregion. Three springs at the southern end of the Ash Meadows spring line (Big, Bole, and Last Chance) have elevated strontium values, which may indicate that they receive some flow from a different origin, such as the Pahrump Valley (Peterman and Stuckless, 1992a, p. 70; Peterman and Stuckless, 1992b, p. 712). High-resolution aeromagnetic surveys conducted over the Amargosa Desert and Pahrump indicate a possible hydraulic connection between Pahrump Valley and the Amargosa Desert through Stewart Valley (Blakely and Ponce, 2001).

Groundwater recharged on the mountain areas of the Ash Meadows basin flows toward the Spotted Range–Mine Mountain structural zone (fig. D–7). It is generally accepted that groundwater in Tikaboo and Emigrant

Valleys and Yucca and Frenchman Flats flows toward a trough in the potentiometric surface beneath Frenchman Flat and the Specter and Spotted Ranges (figs. D–2 and D–7) (Winograd and Thordarson, 1975; Faunt, 1997; D'Agnese and others, 1997). This trough may be a zone of relatively high permeability in the carbonate-rock aquifer associated with the Spotted Range–Mine Mountain structural zone (Carr, 1984; Faunt, 1997; D'Agnese and others, 1998). The Las Vegas Valley shear zone (LVVSZ) bounds the trough on the south and southeast. The flow paths along the trough are directed through the Specter Range area until they encounter the fault at Ash Meadows.

The basin-fill and volcanic-rock aquifers in Emigrant Valley and Yucca and Frenchman Flats (fig. D–7) provide recharge (fig. D–2) to the regional carbonate-rock aquifer by downward percolation (Winograd and Thordarson, 1975; Laczniak and others, 1996). The water chemistry at Indian Springs Valley indicates that these waters have had little opportunity for contact with volcanic rock or basin-fill sediments composed of volcanic rocks indicating that the groundwater beneath Tikaboo and Emigrant Valleys and Yucca and Frenchman Flats is not moving southward toward Indian Springs Valley. The water in the carbonate-rock aquifer in these locations may be moving toward the Amargosa Desert, where the groundwater is generally of mixed chemical character and has high levels of sodium (Schoff and Moore, 1964; Winograd and Thordarson, 1975). Ultimately most of the groundwater discharges at Ash Meadows.

In the Pahranagat section, near the Sheep Range, the DVRFS boundary is uncertain and has been postulated in various locations (Harrill and others, 1988; Bedinger and others, 1989; Harrill and Prudic, 1998; D'Agnese and others, 1997, 2002; Appendix 2, this volume). For this study, the DVRFS model boundary was placed along the Gass Peak thrust (fig. D–5; Appendix 2, this volume), the easternmost feature postulated as a boundary. This places the boundary between the White River groundwater flow system and the DVRFS farther east than in most previous studies. Consequently, the deeper carbonate rocks may allow substantial amounts of water to flow to the White River groundwater flow system to the east. If this occurs, then a groundwater divide should exist somewhere near the Desert Range, and flow into the Ash Meadows basin must occur through or north of the northern part of the Sheep Range (fig. D–7; Appendix 2, this volume). Regional-potential data (Appendix 1, this volume) also indicate that the flow-system boundary should be along a divide in the approximate location of the Desert Range (fig. D–7). If this divide exists, a significant amount of discharge from the Pahranagat section to the east into the White River groundwater system occurs through the carbonate-rock aquifer in the Sheep Range. West of this divide, discharge occurs as throughflow into Indian Springs Valley.

Recharge to the Pahranagat section occurs partly as throughflow from Tikaboo Valley and in the Sheep Range (fig. D–7). Recharge also may occur at the higher mountains of the Spotted, Pintwater, and Desert Ranges (Laczniak and others, 1996). As previously mentioned, hydrochemical data indicate that little or no flow comes into the DVRFS from the Pahranagat Range. Flow that does come into this section is thought to exit through short pathways to the southeast through the Sheep Range (Appendix 2, this volume).

Recharge to the Tikaboo Valley section occurs in the Pahranagat Range (fig. D–7). Although the eastern boundary of the Tikaboo Valley section is aligned along the Pahranagat Range parallel with the boundary of the White River flow system, throughflow may occur along the flow-system boundary at the Pahranagat Range, especially in the south along the Pahranagat shear zone (Winograd and Thordarson, 1975) (fig. D–5). Little is known about water levels or flow directions in the basin-fill sediments. The water in the carbonate-rock aquifer in Tikaboo Valley is thought to be moving toward the Amargosa Desert (Workman and others, 2002). On the basis of recent interpretations of regional hydraulic gradients (Appendix 2, this volume), however, some, if not all, flow occurs out of the eastern boundary into the White River flow system.

Regional groundwater recharged on the Sheep Range and Spring Mountains flows into the Indian Springs section (fig. D–7) from the south and east and into the potentiometric trough (fig. D–2). Recharge also may occur on higher mountains of the Spotted, Pintwater, and Desert Ranges (Laczniak and others, 1996), most of which are underlain by carbonate rocks. Most of the water has had little opportunity for contact with volcanic rock or basin-fill sediments composed of volcanic rocks. As a result, hydrochemical data can be useful in delineating flow paths to and from this region.

Potentiometric data for both the basin-fill and carbonate-rock aquifers in the southern part of Indian Springs Valley indicate a prominent east-trending hydraulic barrier between the Nye County line and Indian Springs (fig. D–2) (Winograd and Thordarson, 1968), corresponding to the LVVSZ (fig. D–7). Because no clastic-rock confining units are known within the upper part of the saturated zone in this area, this flow barrier may be created by the LVVSZ (Winograd and Thordarson, 1975), causing discharge at Indian and Cactus Springs. In addition to Indian and Cactus Springs, discharge from the Indian Springs section occurs as throughflow to the Specter Range. Groundwater flow in the section converges in the carbonate-rock aquifer along the trough in the potentiometric surface (fig. D–2) and travels toward the Amargosa Desert, ultimately discharging at Ash Meadows.

Another flow barrier formed by the juxtaposition of the LCCU and the LCA (Winograd and Thordarson, 1968) is postulated approximately 8 km to the north of the LVVSZ. Potentiometric data in the area indicate that flow may be to the north in the basin-fill sediments and to the west between the two flow barriers in the carbonate-rock aquifer north of the barriers.

Recharge to the Emigrant Valley section occurs as throughflow from the north or precipitation to the Belted and Groom Ranges (fig. D–7). Flow is generally to the south in the basin-fill sediments to Yucca Flat but is disrupted at depth by low-permeability clastic-rock units. Basin-fill aquifers in Emigrant Valley provide recharge to the carbonate-rock aquifer by percolation downward through basin-fill sediments. The western one-half of Emigrant Valley is bordered on the east, south, and southwest by clastic rocks. Geologic mapping indicates that this area of the valley is part of a highly faulted anticline, which, prior to extensional faulting, brought clastic rocks to the surface over a wide region (Winograd and Thordarson, 1968). Gravity surveys indicate that the bedrock beneath western Emigrant Valley is overlain by as much as 1,200 m of basin-fill sediments (Winograd and Thordarson, 1968).

The steep hydraulic gradients on both sides of Emigrant Valley (fig. D–2) are believed to reflect the movement of water through thick clastic-rock confining units (fig. D–4) toward points of lower hydraulic head in Yucca Flat and in the eastern part of Emigrant Valley (Winograd and Thordarson, 1968). The relatively flat hydraulic gradient in Emigrant Valley reflects the large permeability of the basin-fill aquifers. Both the steep and the flat hydraulic gradients probably are caused by a thick sequence of clastic-rock confining units separating the western part of Emigrant Valley from areas of lower groundwater potential to the east and west. The steep hydraulic gradients may be continuous or may represent discontinuous levels within blocks separated by low-permeability faults. Groundwater flow in the carbonate-rock aquifer in Emigrant Valley appears to be moving toward the trough in the potentiometric surface (fig. D–2).

Recharge to the Yucca–Frenchman Flat section is predominantly throughflow from Emigrant Valley to the north and northeast and possibly precipitation on Rainier Mesa and the adjacent Eleana and Belted Ranges (fig. D–7). Water-level contours (fig. D–2) show a southeastern flow component away from Rainier Mesa toward Yucca Flat. The carbonate-rock aquifer beneath the central and northern parts of Yucca Flat is isolated from the carbonate-rock aquifer in adjacent valleys to the north and east by the bordering clastic-rock confining units. Groundwater moving between the basins into the carbonate-rock aquifer would have to pass through and would be controlled by the permeabilities of the clastic-rock confining units (Winograd and Thordarson, 1968, p. 43). Discharge from Yucca and Frenchman Flats occurs primarily as throughflow in the carbonate-rock aquifer toward a trough in the potentiometric surface (fig. D–2) near the Spotted Range–Mine Mountain structural zone (fig. D–7), continuing to the southwest toward the Amargosa Desert.

Recharge to the Specter Range section is mostly from throughflow in the carbonate-rock aquifer along the trough in the potentiometric surface (fig. D–2). The distribution of precipitation and the resulting infiltration indicate that groundwater moves long distances through different HGUs before reaching Ash Meadows. Groundwater flows through the Specter Range section along the trough in the potentiometric surface and utimately discharges at Ash Meadows.

Alkali Flat–Furnace Creek Basin

The Alkali Flat–Furnace Creek basin lies south and west of the Ash Meadows and Pahute Mesa–Oasis Valley basins and covers most of the western one-half of the NTS (fig. D–7). Groundwater in this basin is derived from recharge on Pahute Mesa, Timber and Shoshone Mountains, and the Grapevine and Funeral Mountains. Additional recharge to this basin may occur as throughflow from Sarcobatus Flat, Oasis Valley, and Ash Meadows. Recharged groundwater from throughflow and local recharge moves 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. Subsurface outflow follows the general course of the Amargosa River drainage through a veneer of alluvium near Eagle Mountain into the southern Death Valley subregion (Walker and Eakin, 1963). As with the other basins, the location of the boundary of the Alkali Flat–Furnace Creek basin is neither well established nor fully understood. The Alkali Flat–Furnace Creek basin is divided into four sections: the Fortymile Canyon, Amargosa River, Crater Flat, and Funeral Mountains sections.

Recharge to the Fortymile Canyon section is primarily from throughflow from the volcanic rocks of the eastern part of Pahute Mesa and the western part of Rainier Mesa (fig. D–7). Infiltration of surface runoff in the alluvium of the upper reaches of Fortymile Canyon and Fortymile Wash during periods of moderate to intense precipitation may be another source of locally important recharge (Czarnecki and Waddell, 1984; Laczniak and others, 1996; Savard, 1998; Hevesi and others, 2003). Hydraulic gradients based on sparse water-level data indicate that the principal flow direction in the section is southward from the eastern part of Pahute Mesa and western part of Rainier Mesa. Data from the northern part of this section are insufficient to assess whether flow continues south beneath Timber Mountain or is diverted around it toward Shoshone Mountain, Yucca Mountain, and Jackass Flats. The southern part of the Fortymile Canyon and Wash section includes Yucca Mountain. At and near Yucca Mountain, hydraulic gradients are dominantly upward in the volcanic-rock units from the carbonate-rock aquifer (Luckey and others, 1996). From Fortymile Wash, flow continues southward as throughflow into the Amargosa River section (Laczniak and others, 1996).

Recharge to the Amargosa River section is predominantly by throughflow in the basin-fill sediments from the Oasis Valley, Crater Flat, Fortymile Canyon and Wash, and Specter Range sections (fig. D–7). Recharge to the carbonate-rock aquifer also occurs by throughflow from the Specter Range and from the Fortymile Canyon sections. In the northwestern part of the Amargosa River section, intermediate groundwater movement is dominantly lateral and downward toward regional flow paths (Czarnecki and Waddell, 1984; Sinton, 1987; Kilroy, 1991). In the south-central parts of the basin, near the Nevada-California border, regional groundwater movement is mostly upward from the carbonate-rock aquifer into the intermediate system and toward discharge areas along the Amargosa River, Carson Slough, and Alkali Flat (Czarnecki and Waddell, 1984; Czarnecki, 1997). Hydrochemical data suggest that water in the carbonate-rock aquifer to the north and northeast and in volcanic-rock aquifers to the north and northwest flows toward the Amargosa Desert, where groundwater generally is of mixed chemical character and has a large amount of sodium (Schoff and Moore, 1964).

Hydraulic and hydrochemical data indicate that water in the regional flow system in the southern part of the Amargosa Desert (fig. D–7) either may flow southwest toward Death Valley through fractures in the southeastern end of the Funeral Mountains or flow southward and toward the surface at Alkali Flat (or Franklin Lake playa), deflected by the low-permeability quartzites of the Resting Spring Range (fig. D–7) (Czarnecki and Waddell, 1984; Czarnecki and Wilson, 1991). The carbonate rocks beneath the Funeral Mountains also might provide preferential conduits or drains for flow from the basin-fill sediments beneath the Amargosa Desert toward Death Valley (Czarnecki and Waddell, 1984; Luckey and others, 1996, p. 14).

Recharge to the Funeral Mountains section is thought to be predominantly from throughflow in the carbonate-rock aquifer in the southern part of the Funeral Mountains (fig. D–7). Additional groundwater enters Death Valley as throughflow from Panamint Valley and the Owlshead Mountains in the southern Death Valley subregion. Local precipitation in the Panamint Range and in the Black and Funeral Mountains, and to a lesser extent in the Greenwater Range, supports mountain-front recharge as surface water seeps into the ground when it reaches alluvial fans ringing the floor of Death Valley. In addition, a small amount of throughflow originating in the northern and southern Death Valley subregions may occur in the relatively fine-grained basin-fill sediments in Death Valley. The Funeral Mountains section contains the major discharge area at the Furnace Creek area for the Alkali Flat–Furnace Creek basin.

The Alkali Flat–Furnace Creek basin supplies water to rural communities in the Amargosa Desert and to private recreational establishments and Federal facilities within Death Valley National Park, Calif. (Laczniak and others, 1996; see fig. A–1)). Domestic and smaller scale irrigation withdrawal started in the 1970s and continues to the present in the western Amargosa Desert. The withdrawal has caused local water-level declines. Withdrawal connected with mining operations south of Beatty has caused lower water levels in the northwestern arm of the Amargosa Desert (Moreo and others, 2003).

The main discharge area in the basin is the springs in the Furnace Creek area (fig. D–7) including Texas, Travertine, and Nevares springs (see fig. C–2). Hydrochemical data indicate that spring flow in the major springs at the Furnace Creek area likely derives from the carbonate-rock aquifer (Winograd and Thordarson, 1975, p. C95). Similar hydrochemistry between spring waters at Ash Meadows and the Furnace Creek area (Czarnecki and Wilson, 1991; Steinkampf and Werrell, 2001) indicate a hydraulic connection between these two discharge areas through the regional carbonate-rock aquifer by way of large-scale fractures or channels in the carbonate-rock aquifer (Winograd and Pearson, 1976).

Downgradient from the Furnace Creek springs, the remaining groundwater and reinfiltrated spring flow moves toward the Death Valley saltpan and either is transpired by stands of mesquite on the lower part of the Furnace Creek fan or is evaporated from the saltpan in Badwater Basin (fig. D–7). The Death Valley saltpan is the largest playa in the region (fig. D–3), and despite the low rate of ET from the saltpan proper, the great area of this feature results in a significant amount of discharge (DeMeo and others, 2003). In addition, the saltpan is surrounded by alluvial fans and numerous springs fringed with vegetation. Groundwater is shallow near the distal end of most of the fans sloping from the mountains ringing Death Valley and in the areas between them. Marshes, phreatophytes, and small springs that lie at the base of the fans discharge local recharge from the surrounding mountains and throughflow from adjacent basins.

Southern Death Valley Subregion

Groundwater in the southern Death Valley subregion primarily is derived from recharge at the Spring Mountains and to a lesser extent from recharge at the Nopah, Kingston, and Greenwater Ranges (fig. D–8). Groundwater also may be entering the system as throughflow in the basin-fill sediments of the Silurian Valley and valleys adjacent to the Owlshead Mountains (Appendix 2, this volume). Additional minor groundwater inflow may occur across the boundary from the Alkali Flat–Furnace Creek basin south of Alkali Flat (fig. D–8). The largest discharge area in the subregion is in Pahrump Valley, which contains a broad playa with several springs. The subregion contains four sections: Pahrump Valley, Shoshone-Tecopa, California Valley, and Ibex Hills, each with a significant discharge area. The Valjean section of D'Agnese and others (1997) is thought to have very little flow into the DVRFS model domain and is not used in this study (Appendix 2, this volume). The interconnection between the four sections is much more apparent than sections in the northern and central subregions.

Before extensive development, the playa area in Pahrump Valley contained some phreatophytic vegetation and was surrounded by sparse shrubland vegetation rising into alluvial fans. Groundwater withdrawals accompanying large-scale agricultural development in the Pahrump Valley section has caused cessation of flow of some major springs in the area during withdrawal, with the gradual recovery of spring flow after some withdrawal stopped. Historically, Manse and Bennetts Springs discharged along the base of the broad alluvial fans at the foot of the Spring Mountains. Groundwater withdrawal in the valley caused these springs to cease flowing in the 1970s. In the late 1990s, Manse Spring began to flow again, perhaps due to changes in the scale of agriculture and agricultural practices in the valley. Withdrawal in the valley does continue for domestic uses and small-scale agriculture uses (Moreo and others, 2003).

Groundwater in the Pahrump Valley section that does not discharge at Pahrump Valley flows either west toward Stewart Valley and the northern end of Chicago Valley, or southwest toward California Valley (fig. D–8). Direct groundwater flow to Death Valley from Pahrump Valley is unlikely because of low-permeability quartzites of the Resting Spring Range (Winograd and Thordarson, 1975; Grose, 1983, Sweetkind and others, 2001) that may bifurcate groundwater flow. Some of the groundwater flowing toward the south and west is consumed by ET from playas in Stewart and Chicago Valleys.

In the Shoshone-Tecopa section, recharge predominantly is throughflow from adjacent sections with some contribution from local recharge in the Nopah Range (fig. D–8). Groundwater throughflow from Pahrump Valley mixes with groundwater flowing south from Alkali Flat. Discharge occurs from ET and springs along the flood plain of the Amargosa River between the towns of Shoshone and Tecopa, Calif. Discharge in the Shoshone-Tecopa section may be from (1) basalt flows to the west damming shallow groundwater, (2) normal faults beneath the Amargosa River south of Eagle Mountain forcing groundwater upward (Steinkampf and Werrell, 2001, p. 20), and(or) (3) a shallow (less than 10 km deep) intrusive body influencing the flow of groundwater (Steinkampf and Werrell, 2001, p. 20). Groundwater that does not discharge in the Shoshone-Tecopa area may continue flowing to the southwest into the Ibex Hills section through faulted and fractured crystalline rocks. Groundwater continues flowing south in the alluvium along the Amargosa River channel into the California Valley section.

In addition to this throughflow from Pahrump Valley, recharge to the California Valley section is from precipitation on the Kingston Range and groundwater that flows south from the Shoshone-Tecopa section (fig. D–8). South of Tecopa, Calif., a structural uplift brings groundwater to the surface and feeds a perennial reach of the Amargosa River. Groundwater leaves the California Valley section as surface-water flow or throughflow in the alluvium along the Amargosa River.

In addition to throughflow from the Shoshone-Tecopa section, flow into the Ibex Hills section also occurs along the Amargosa River channel as surface water or groundwater in the associated alluvium (fig. D–8). Some additional groundwater may enter the section as throughflow from Valjean, Shadow, and Silurian Valleys (which drain an extensive area south of the Kingston Range) and adjacent to the Owlshead Mountains. Discharge occurs primarily as ET and spring flow in the Saratoga Springs area. This area is supported by groundwater discharge from the regional carbonate-rock aquifer and includes adjacent areas of shallow groundwater along the flood plain of the Amargosa River. A small amount of groundwater flow may continue north past Saratoga Springs to the central Death Valley subregion and discharge at Badwater Basin.

Surface-Water Hydrology

In the DVRFS region, perennial streamflow is sparse. Most surface water in the region is either runoff or spring flow discharge. Precipitation falling on the slopes of the mountains (such as the Panamint Range or the Black and Funeral Mountains) forms small, intermittent streams that quickly disappear and infiltrate as groundwater recharge. In addition, several streams originate from snowmelt in the high altitudes of the Spring Mountains. Both of these types of streams have highly variable base flows and in dry years have almost imperceptible discharges. Springs maintain perennial flow for short distances in some of the drainages.

Surface-water flows in the DVRFS region have been categorized on the basis of hydrographic areas or hydrologic units (fig. D–9) that are the basic units used by State and local agencies for water-resources planning (Cardinalli and others, 1968; Eakin and others, 1976; and Seaber, 1987). Hydrologic units are delineated primarily on the basis of topography and geologic structures and generally correspond to major surface drainages.

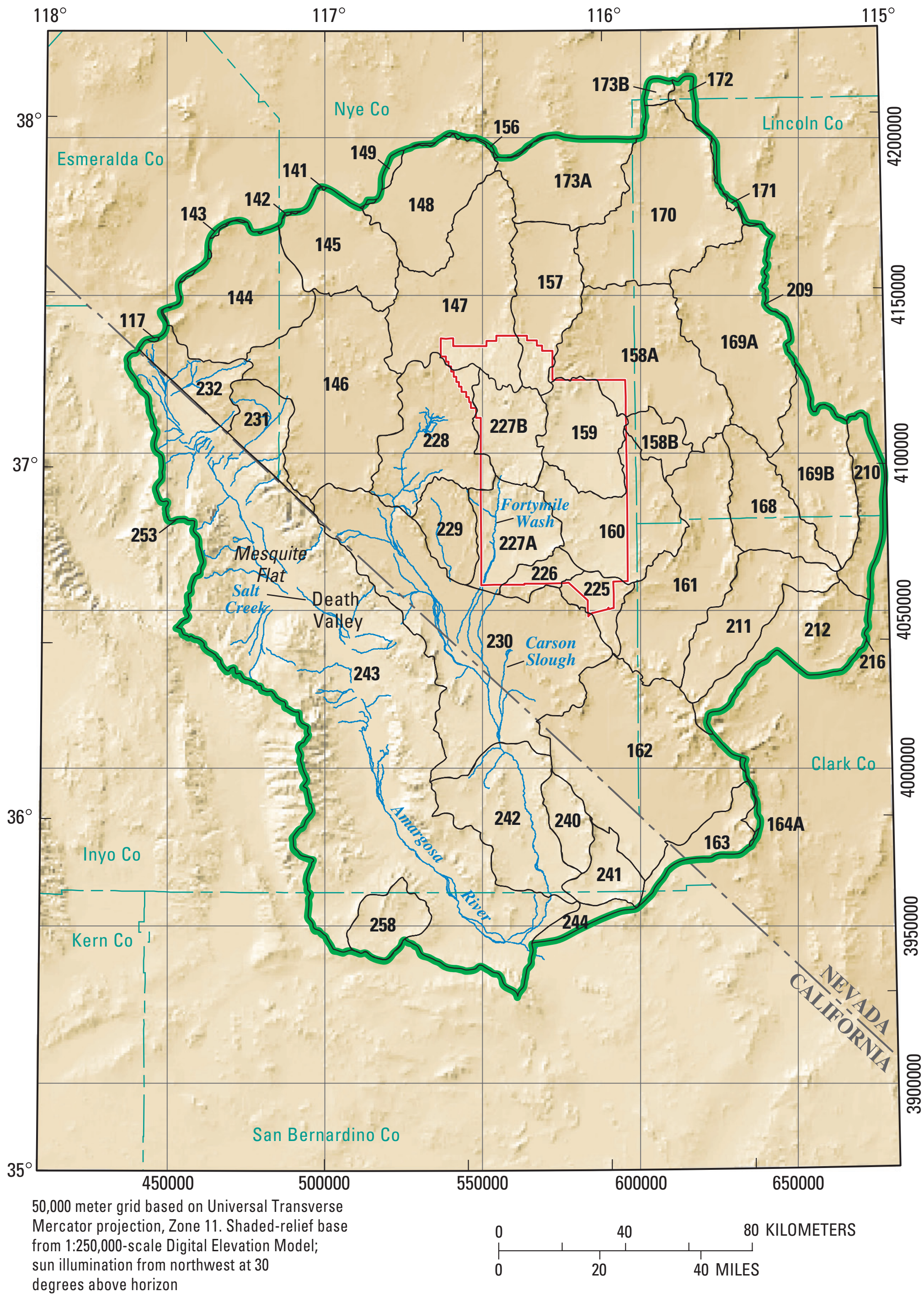
Drainage Areas

The Death Valley watershed contains two primary drainage basins—the Amargosa River basin in the south and the Salt Creek basin in the north. The Amargosa River Basin drainage area composes approximately two-thirds of the 22,100-km^2 Death Valley watershed and has the largest drainage basin discharging into Death Valley (Grasso, 1996). The Amargosa River is the only large perennial stream in the DVRFS region, originating in the mountains of southwestern Nevada and flowing south and west, terminating in the sinks and playas of Death Valley (fig. D–9). Despite the large drainage area, most of the Amargosa River and its tributaries are ephemeral.

Salt Creek drains the northwest part of Death Valley, an area of about 5,700 km^2 (fig. D–9). Although Salt Creek drains only one-third as much area as does the Amargosa River, it discharges more surface water to the Death Valley saltpan than does the Amargosa River (Hunt, 1975). Groundwater discharging as seeps and spring flow from Mesquite Flat feeds Salt Creek (Hunt, 1975). Though Mesquite Flat is without perennial surface water, an extensive growth of phreatophytes is supported by shallow groundwater.

Springs

There are four principal kinds of springs in the DVRFS model domain: those discharging along (1) high-angle faults, (2) low-angle faults, (3) low-permeability structural barriers, and (4) lithologic gradations into less-permeable material (Hunt



Hydrologic unit and code

117	Fish Lake Valley
141	Ralston Valley
142	Alkali Spring Valley
143	Clayton Valley
144	Lida Valley
145	Stonewall Flat
146	Sarcobatus Flat
147	Gold Flat
148	Cactus Flat
149	Stone Cabin Valley
156	Hot Creek Valley
157	Kawich Valley
158	Emigrant Valley **A** Groom Lake Valley **B** Papoose Lake Valley
159	Yucca Flat
160	Frenchman Flat
161	Indian Springs Valley
162	Pahrump Valley
163	Mesquite Valley
164A	Northern Ivanpah Valley
168	Three Lakes Valley (northern part)
169	Tikaboo Valley **A** Northern part **B** Southern part
170	Penoyer Valley
171	Coal Valley
172	Garden Valley
173A	Southern Railroad Valley
173B	Northern Railroad Valley
209	Pahranagat Valley
210	Coyote Spring Valley
211	Three Lakes Valley (southern part)
212	Northern Las Vegas Valley
216	Garnet Valley
225	Mercury Valley
226	Rock Valley
227	Fortymile Canyon **A** Jackass Flats **B** Buckboard Mesa
228	Oasis Valley
229	Crater Flat
230	Amargosa Desert
231	Grapevine Canyon
232	Oriental Wash
240	Chicago Valley
241	California Valley
242	Lower Amargosa Valley
243	Death Valley
244	Valjean Valley
253	Racetrack Valley
258	Lost Lake–Owl Lake Valley

EXPLANATION

Death Valley regional groundwater flow system model boundary

Nevada Test Site boundary

Figure D–9. Hydrologic units for the Death Valley regional groundwater flow system (modified from Cardinalli and others, 1968; Eakin and others, 1976; and Seaber and others, 1987).

and others, 1966). The largest and most significant springs for this study are those discharging along the high-angle faults, for example, Travertine, Texas, and Nevares Springs along the Furnace Creek fault zone (Hunt and others, 1966), and the springs at Ash Meadows near the Gravity fault (fig. D–10) (Laczniak and others, 1999). In the mountains, springs discharge at low-angle faults no more than a few gallons per minute (Hunt, 1975). Most of the springs in the Panamint Range are of this type. The third type of spring occurs where groundwater is ponded behind a low-permeability structural barrier, such as the spring area at Mesquite Flat. The fourth type of spring is found at the edge of the Death Valley floor where groundwater is ponded in the gravel and sand of the fans as they grade into silt under the valley floor. Larger volume and higher temperature springs that occur along major faults are generally considered to be regional springs.

Paleohydrology

Groundwater flow systems respond to and change with climate. The modern groundwater flow system may not be in equilibrium with the modern climate and most likely contains relics of past climates. Forester and others (1999) indicate that during the last glacial cycle (peaking 12,000 years ago [12 ka]), moisture fluxes were greater than current fluxes, and water tables were higher throughout the region (Quade and others, 1995). There is strong evidence that, during Quaternary time, there has been a steady decline in the regional potentiometric surface (Winograd and Szabo, 1988). Stands of mesquite in Death Valley, which are dependent on groundwater of fairly good quality, have been dying and are not being replaced, which may indicate that the water supply is continuing to diminish. Whether this decline is because of a decrease in the supply of water or an increase in salinity, or both, is uncertain (Hunt, 1975).

Fossil, isotopic, and petrographic data provide evidence of past changes in precipitation, temperature, and evaporation, which are the manifestations of large-scale climate changes. In this study, climate change is of interest because of the effect of past climates on water levels. For example, plant macrofossils in the DVRFS region indicate that the mean annual precipitation in the past 40 to 10 ka was variable but was typically as much as twice the modern mean annual precipitation (Forester and others, 1999). These plant macrofossil data, together with aquatic fossils, indicate lower mean annual temperature than today (Forester and others, 1999). The increased precipitation and cooler temperatures resulted in a greater than modern level of effective moisture. Greater than modern levels of effective moisture resulted in regional aquifer recharge that was much higher during past pluvial periods (40 to 10 ka; Forester and others, 1999) than today (Benson and Kleiforth, 1989).

Evidence for a higher regional water table at some time in the past has been suggested on the basis of many lines of evidence. J.B. Paces (U.S. Geological Survey, written commun., 2004) points out that records of climate change that may indicate higher water levels can be categorized into three groups: (1) surface features (paleolimnology, paleobotany, and sedimentology); (2) saturated-zone features (paleohydrographs and paleorecharge); and (3) unsaturated-zone features (pore water and secondary hydrogenic minerals). The data indicate that the water table may have been 10 to 30 meters (m) higher in the past; some researchers postulate the water table may have been as much as 120 m higher.

Extensive paleodischarge deposits and paludal sediments were identified by Swadley and Carr (1987). The location and description of these deposits were refined on the basis of secondary mineral occurrences (Levy, 1991) and strontium isotopic variations from calcite collected from boreholes (Marshall and others, 1993) by Forester and others (1999) and Paces and Whelan (2001). Synchronous paleodischarge at numerous paleodischarge sites distributed over a broad area with heterogeneous hydrogeological conditions indicates the likelihood of a widespread rise in the regional water table (Forester and others, 1999) (fig. D–10). Under these wetter climate conditions, discharge from all sources probably greatly exceeded that which occurred during historical time.

Wetlands from the past pluvial periods of 40 to10 ka, such as those represented by the deposits at Cactus, Cow Creek, and Tule Springs, were supported by discharge from both the groundwater and surface-water systems. Increased recharge in the Spring Mountains and Sheep Range probably resulted in spring discharge from the alluvial fans at the foot of the mountain ranges.

Deposits in the northern part of Amargosa Desert and the southern part of Crater Flat (fig. D–10) probably also represent an area of focused groundwater discharge during the late Pleistocene (40–12 ka) (Forester and others, 1999). Deposits north of Death Valley Junction, Calif., adjacent to the southern end of the Funeral Mountains (fig. D–10), show an interplay of surface flow and spring discharge as do the deposits in the Amargosa Desert. Interpretations of paleodischarge deposits are not available for Ash Meadows. Quade and others (1995) have identified and studied late Pleistocene wetland deposits in Pahrump Valley. Extensive spring-discharge and wetland deposits are known from the Pahrump Valley, and according to Quade and others (1995), deposits from about 21 ka and older probably do exist there.

Pluvial lakes occupied many basins in the central and eastern Great Basin during the late Pleistocene (Forester and others, 1999). Within the region, shallow (less than 1.3 m deep) lakes existed in Gold Flat and Emigrant and Kawich Valleys. Fortymile Wash and the Amargosa River were probably perennial streams that helped supply Lake Manly in Death Valley. To produce and maintain this lake would have required either (1) a sizable increase in the volume of precipitation over the saltpan and runoff from the watershed, (2) a substantial decrease in temperature to reduce annual lake evaporation, or (3) a combination of these climatic changes (Grasso, 1996).

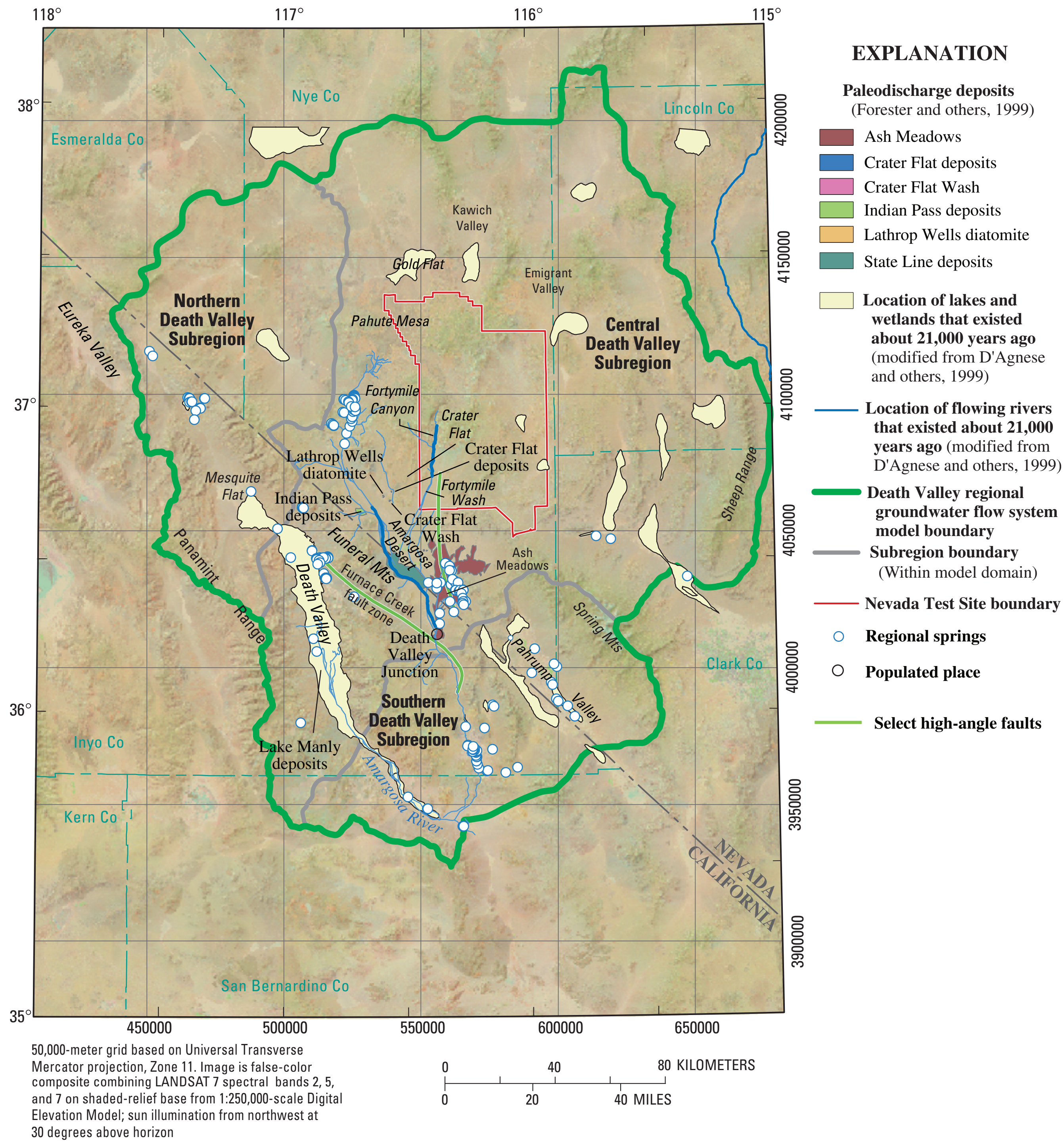


Figure D–10. Location of paleodischarge areas and regional springs in the Death Valley regional groundwater flow system region.

Hydrologic models that are based on assumed increased recharge during Pleistocene time (Czarnecki, 1985; D'Agnese and others, 1999) seem to confirm these observations. D'Agnese and others (1999) have reported on a conceptual model of the paleohydrology, based on their climate simulation of the Yucca Mountain Project/Hydrologic Resource Management Program (YMP/HRMP) regional groundwater flow model (D'Agnese and others, 1997). In this simulation, the region was assumed to be much cooler and wetter than present, and the lakes and greater discharges described above were supported. It must be remembered, however, that these models have many limitations, not the least of which is the representation of the system as steady state.

Summary

Groundwater in the DVRFS region occurs in several interconnected, extremely complex groundwater flow systems. The water moves along relatively shallow and localized flow paths that are superimposed on deeper, regional flow paths. Regional groundwater flow is predominantly through conduits in the carbonate rocks. This flow field is influenced by complex geologic structures created by regional faulting and fracturing that can create conduits or barriers to flow.

Infiltration of precipitation and runoff on high mountain ranges is the largest source of groundwater recharge. Springs and evapotranspiration are the dominant natural groundwater discharge processes. Discharge related to human activities is associated with groundwater pumping for agricultural, commercial, and domestic uses and is not negligible.

The water table is the upper boundary of the flow system and both no-flow and flow boundaries exist at the lateral extent of the defined flow system. The lower boundary surface of the Death Valley regional groundwater flow system (DVRFS) model domain is the depth at which groundwater flow is dominantly horizontal or parallel to the lower surface and generally corresponds with the upper surface of low-permeability basement rock. Groundwater inflow to the DVRFS model domain occurs in the vicinities of Garden, Coal, Stone Cabin, the southern part of Railroad, Eureka, and Saline Valleys, and the Panamint Range, with possibly small amounts in the Owlshead Mountains. Groundwater outflow occurs at the Sheep Range and parts of the Pahranagat Range, and the western part of Las Vegas Valley and, to a small degree, Silurian Valley.

The region can be subdivided into the northern, central, and southern subregions. Groundwater flows between these subregions, each which of has distinctive characteristics.

In the northern Death Valley subregion, water levels indicate that much of the groundwater flow is shallow, as the area is underlain by low-permeability bedrock. Groundwater flow is controlled by northeast-southwest-trending structural zones through the mountain ranges east of Death Valley. Groundwater entering the subregion as throughflow from the northern boundary or recharge from precipitation flows south to Sarcobatus Flat and Death Valley. Some of this flow discharges at Grapevine and Staininger Springs. These springs result from the intersection of high- and low-permeability structures.

The central Death Valley subregion includes the major discharge areas of Oasis Valley, Ash Meadows, and Alkali Flat–Furnace Creek. These major discharge areas result from flow paths that are complicated by groundwater possibly entering the subregion in the vicinities of Stone Cabin, Garden, Coal, and the southern part of Railroad Valleys. Groundwater flow is generally from Pahute Mesa toward Oasis Valley or from the north toward the potentiometric trough north-northeast of Ash Meadows. The major flow paths in the subregion appear to coincide with high-permeability zones created by regional fault or fracture zones. Some of the groundwater that originates as recharge in mountain areas or as inflow to the subregion discharges at Ash Meadows. Some continues south and discharges in the Alkali Flat–Furnace Creek basin.

Groundwater movement in the central Death Valley subregion is dominantly lateral and downward toward regional flow paths in the northwestern parts of the Amargosa Desert. Near Yucca Mountain and in areas immediately to the south, vertical gradients are dominantly upward from the carbonate-rock aquifer into the intermediate system and flow is toward discharge areas to the south and southwest. Groundwater in the southern Amargosa Desert may either flow through fractures in the southeastern end of the Funeral Mountains and discharge in the Furnace Creek area or flow southward and discharge at Alkali Flat.

The southern Death Valley subregion is dominated by flow derived primarily from precipitation and subsequent infiltration on the Spring Mountains. Water moves toward the major discharge areas in Pahrump Valley. Springs on the distal edges of alluvial fans in Pahrump Valley have diminished flow, which might result from local groundwater use. Groundwater that is not intercepted in Pahrump Valley flows southwest toward discharge areas in Chicago and California Valleys and, ultimately, Saratoga Springs.

In the DVRFS region, the entire groundwater system is not in equilibrium. The system has been modified by generally local pumping in (1) Pahrump Valley, (2) Amargosa Desert, (3) Penoyer Valley, and, to a lesser extent, (4) the Nevada Test Site. Although there are virtually no perennial streams in the region, there is evidence for surface-water features, such as perennial streams, lakes, and marshes as well as higher groundwater levels, resulting from wetter climates in the past. Residual effects from past climate change during the Pleistocene, although identifiable in some areas, are thought to be negligible.

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