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Ground-Water Discharge Determined from Measurements of Evapotranspiration, Other Available Hydrologic Components, and Shallow Water-Level Changes, Oasis Valley, Nye County, Nevada

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per day	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/day)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
gallons per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
pounds per cubic foot (lbs/ft^3)	27.680	grams per cubic centimeter
pounds per square inch (lbs/in^2)	6.895	kilopascals
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
watts per square foot (W/ft^2)	10.76	watts per square meter

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)] + 32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F - 32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Note: English units are used throughout this report, except in instances where a measurement has no common English-unit equivalent.

ACRONYMS AND SYMBOLS

A	Cross-sectional area
BWSD	Beatty Water and Sanitation District
DGV	Moderately dense to dense grassland vegetation
DMV	Dense meadow and woodland vegetation
DWV	Dense wetland vegetation
E	Rate of water evaporation
ERP	Environmental Restoration Program
ET	Evapotranspiration
G	Subsurface heat flux
H	Sensible heat flux
K	Hydraulic conductivity
MSAVI	Modified soil-adjusted vegetation index
MBS	Moist bare soil
NDWR	Nevada Division of Water Resources
NTS	Nevada Test Site
OWB	Open water body
Q	Quantity of ground-water flow
R_n	Net radiation
SAV	Submerged and sparse emergent aquatic vegetation
SGV	Sparse to moderately dense grassland vegetation
SSV	Sparse to moderately dense shrubland vegetation
SWNVF	Southwestern Nevada Volcanic Field
T	Temperature
TM	Thematic mapper
UCL	Unclassified
USDOE	U.S. Department of Energy
USGS	U.S. Geological Survey
λ	Latent heat of vaporization for water
λE	Latent heat flux

Ground-Water Discharge Determined from Measurements of Evapotranspiration, Other Available Hydrologic Components, and Shallow Water-Level Changes, Oasis Valley, Nye County, Nevada

By Steven R. Reiner, Randell J. Laczniak, Guy A. DeMeo, J. LaRue Smith, Peggy E. Elliott, Walter E. Nylund, *and* Christopher J. Fridrich

ABSTRACT

Oasis Valley is an area of natural ground-water discharge within the Death Valley regional ground-water flow system of southern Nevada and adjacent California. Ground water discharging at Oasis Valley is replenished from inflow derived from an extensive recharge area that includes the northwestern part of the Nevada Test Site (NTS). Because nuclear testing has introduced radionuclides into the subsurface of the NTS, the U.S. Department of Energy currently is investigating the potential transport of these radionuclides by ground water flow. To better evaluate any potential risk associated with these test-generated contaminants, a number of studies were undertaken to accurately quantify discharge from areas downgradient in the regional ground-water flow system from the NTS. This report refines the estimate of ground-water discharge from Oasis Valley.

Ground-water discharge from Oasis Valley was estimated by quantifying evapotranspiration (ET), estimating subsurface outflow, and compiling ground-water withdrawal data. ET was quantified by identifying areas of ongoing ground-water ET, delineating areas of ET defined on the basis of similarities in vegetation and soil-moisture conditions, and computing ET rates for each of the delineated areas. A classification technique using spectral-reflectance characteristics determined from satellite imagery acquired in 1992 identified eight unique areas of ground-water ET. These areas encompass about 3,426 acres of sparsely to densely vegetated grassland, shrubland, wetland, and open water. Annual ET rates in Oasis Valley were computed with energy-budget methods using micrometeorological data collected at five sites. ET rates range from 0.6 foot per year in a sparse, dry saltgrass environment to 3.1 feet per year in dense meadow vegetation.

Mean annual ET from Oasis Valley is estimated to be about 7,800 acre-feet. Mean annual ground-water discharge by ET from Oasis Valley, determined by removing the annual local precipitation component of 0.5 foot, is estimated to be about 6,000 acre-feet. Annual subsurface outflow from Oasis Valley into the Amargosa Desert is estimated to be between 30 and 130 acre-feet. Estimates of total annual ground-water withdrawal from Oasis Valley by municipal and non-municipal users in 1996 and 1999 are 440 acre-feet and 210 acre-feet, respectively. Based on these values, natural annual ground-water discharge from Oasis Valley is about 6,100 acre-feet. Total annual discharge was 6,500 acre-ft in 1996 and 6,300 acre-ft in 1999. This quantity of natural ground-water discharge from Oasis Valley exceeds the previous estimate made in 1962 by a factor of about 2.5.

Water levels were measured in Oasis Valley to gain additional insight into the ET process. In shallow wells, water levels showed annual fluctuations as large as 7 feet and daily fluctuations as large as 0.2 foot. These fluctuations may be attrib-

uted to water loss associated with evapotranspiration. In shallow wells affected by ET, annual minimum depths to water generally occurred in winter or early spring shortly after daily ET reached minimum rates. Annual maximum depths to water generally occurred in late summer or fall shortly after daily ET reached maximum rates. The magnitude of daily water-level fluctuations generally increased as ET increased and decreased as depth to water increased.

INTRODUCTION

Oasis Valley is one of only a few areas of natural discharge within a large, regionally extensive ground-water basin known as the Death Valley regional ground-water flow system (fig. 1). This flow system, as defined by Harrill and others (1988), extends hundreds of miles over a geologically complex, arid to semi-arid region of southern Nevada and adjacent California. Centrally located within the boundaries of this flow system is the Nevada Test Site (NTS), a Federal facility that for more than 40 years was used to test nuclear devices. This nuclear testing released significant quantities of radionuclides to the subsurface of parts of the NTS. Radionuclides in ground water beneath the NTS may have the potential to migrate from the NTS in the direction of ground-water flow. Ground water beneath the NTS generally moves southward and westward toward one of four areas of major natural ground-water discharge: (1) Oasis Valley, (2) Ash Meadows, (3) Alkali Flat, and (4) Death Valley (Winograd and Thordarson, 1975; Waddell and others, 1984; Laczniak and others, 1996).

Contaminants generated at the NTS are the subject of a long-term program of investigation and remediation by the U.S. Department of Energy (USDOE) under its Environmental Restoration Program (ERP). As part of this program, the USDOE is evaluating potential transport of radionuclides from the NTS to adjacent areas. This objective requires that the potential for contaminant migration be determined and the hydrologic factors controlling their transport be reasonably well known. Because the rate and direction of ground-water flow away from the NTS is controlled in part by the location and amount of water leaving the flow system, any accurate assessment of contaminant migration is predicated on having a sound understanding of ground-water discharge. Although the general locations of the discharge areas are known, much uncertainty exists as to the precise amount of water leaving the flow system at each of these locations. To reduce this uncertainty, the U.S. Geological Survey (USGS), in cooperation with the USDOE, began a series of studies in 1993 designed to refine and improve previous estimates of ground-water discharge throughout the region.

Oasis Valley is one of the discharge areas chosen for study based in part on (1) the area's proximity to past locations of underground testing (a distance of less than 17 miles, figs. 1 and 2); (2) the potential for rapid water and contaminant transport through the highly fractured volcanic aquifers that contribute water to the area (Fridrich and others, 1999); (3) the availability of data about Oasis Valley acquired by previous and ongoing studies; and (4) the use of water in the area by ranches in upper Oasis Valley and by residents of Springdale and Beatty, Nev. Related investigations to refine estimates of ground-water discharge at other major discharge areas influencing ground-water flow away from the NTS have been completed (Laczniak and others, 1999, 2001) or are in progress.

Purpose and Scope

The purpose of the study is to refine and improve the current estimate of ground-water discharge from Oasis Valley. This report presents a new estimate of ground-water discharge computed from evapotranspiration (ET) rates, subsurface outflow, and ground-water withdrawal. ET rates were calculated from field measurements of localized meteorological information (referred to as micrometeorological data) and extrapolated over the study area on the basis of similarities in vegetation, soil-moisture characteristics, and depth to ground water. Subsurface outflow was estimated using Darcy's Law and estimates of hydraulic gradient, aquifer geometry, and hydraulic conductivity. Ground-water withdrawal was compiled from local public water supply records and estimates of non-municipal use. This report presents the results of the study and describes the general approach used to estimate ground-water discharge.

The method used to determine ET rates required the collection of micrometeorological data and water levels on a nearly continuous basis. This intense data-collection effort generated a substantial amount of climatic, ecological, and hydrologic data. This report is not intended to be a comprehensive data compilation, and presents only those data most pertinent to its final conclusions. Other data specific to the study can be found in previously published reports by Reiner and others (1999) and the USGS (1996–2000), or can be requested from the Las Vegas Subdistrict Office of the USGS.

Acknowledgements

The authors express their appreciation to all agencies that cooperated in this study. These agencies include the U.S. Department of Energy (USDOE), Bureau of Land Management (BLM), Beatty Water and Sanitation District (BWSD), Beatty General Improvement District, and Nevada Division of Water Resources (NDWR). The authors also thank the many individuals who contributed to the completion of the study. In particular, David L. Berger, Donald H. Schaefer, and Armando R. Robledo of the USGS provided valuable assistance with geophysical surveys and logging. The authors also thank the many private landowners and residents in the area, including Mr. and Mrs. Glenn L. Coffer, Mr. David Spicer, Ms. Sharon Patton-Bailey, and Mr. Ed Peacock, who allowed access to their property and extended their hospitality to project personnel. The genuine interest expressed by all involved in this study is greatly appreciated.

Location and Dominion

Oasis Valley is in southern Nye County, Nev. (figs. 1 and 2), about 40 mi north of the Death Valley National Park headquarters near Furnace Creek Ranch, California, and 120 mi northwest of Las Vegas, Nev. The boundaries of the Oasis Valley Hydrographic Area, as established by Rush (1968), encompass about 300,000 acres of desert uplands and spring-fed oases (fig. 2). About 40,000 acres of this area overlies a valley-fill aquifer; the valley floor contains about 3,800 acres of phreatophytes that discharge ground water by ET (Malmberg and Eakin, 1962). The BLM administers most of the land within the area, and the remaining acreage is held by private citizens and local governments.

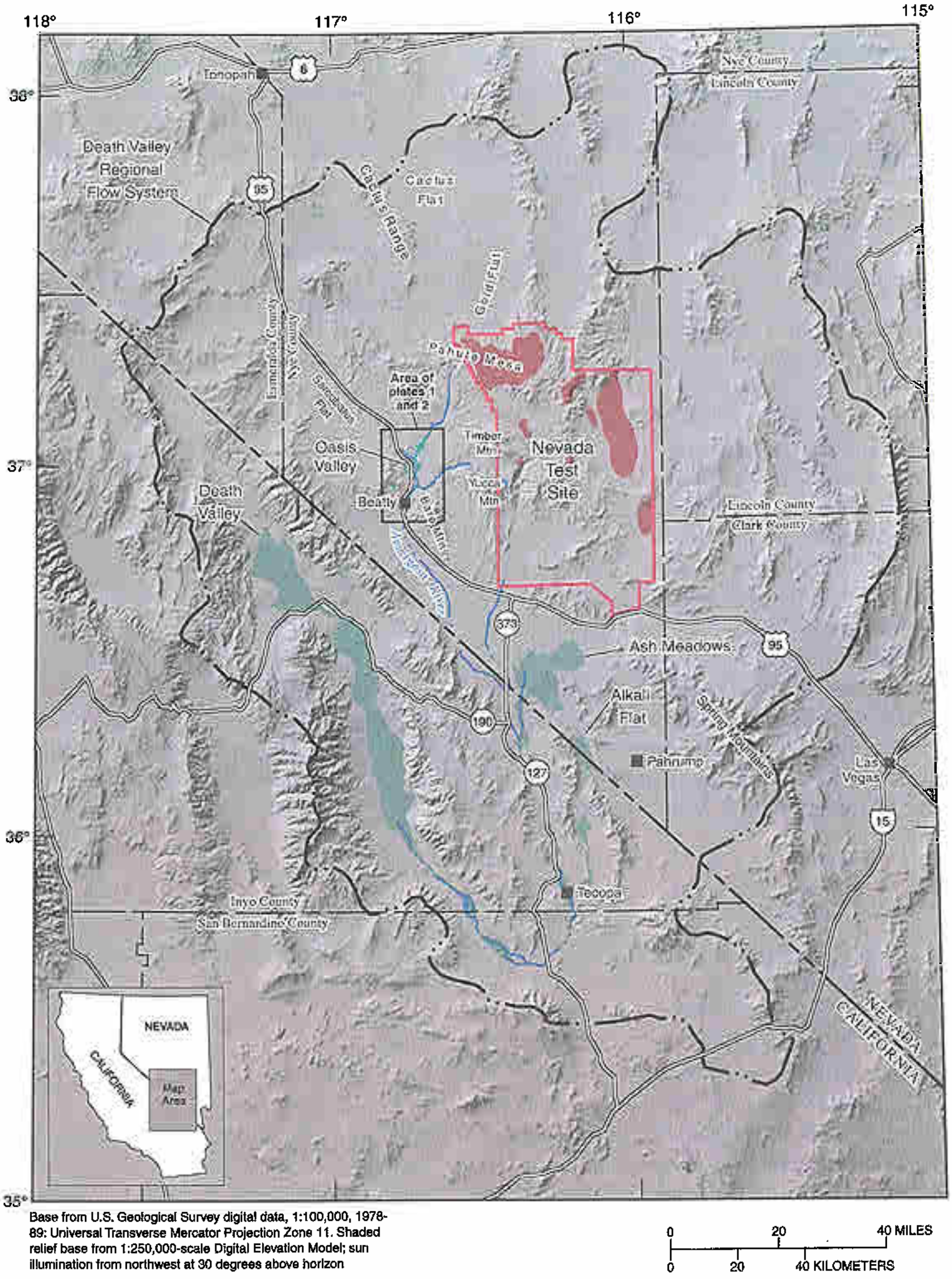
Description and Setting

Oasis Valley lies within the southern part of the Great Basin, an internally drained subdivision of the Basin and Range physiographic province (Fenneman, 1931). The predominant physiographic features of the Basin and Range are linear mountain ranges separating broad, elongated valleys, formed in response to a long and still active period of crustal extension. Large vertical displacements along faults offset bedrock blocks that topographically isolate north-trending mountain ranges from similarly trending sediment-filled valleys (fig. 2). Most of the ranges in the general region are composed of pre-Cenozoic rocks of diverse age and lithology. Paleozoic carbonate and siliceous rocks and Tertiary volcanic rocks constitute the primary rock type of the hills, ridges, and mountain ranges in the area. The intermontane basins are filled with (1) unconsolidated clay, silt, sand, gravel, and boulders; and (2) semi-consolidated to consolidated conglomerate, sandstone, siltstone, claystone, lacustrine limestone, and interbedded volcanic ash and lava flows.

The Oasis Valley Hydrographic Area borders Gold Flat to the north, Sarcobatus Flat to the west, Amargosa Desert, Crater Flat, Yucca Mountain to the south, and Timber Mountain and Pahute Mesa to the north and east (Rush, 1968; fig. 2). The Oasis Valley Hydrographic Area does include the western part of Gold Flat and parts of western and central Pahute Mesa (Laczniak and others, 1996).

Oasis Valley is located in the south-central and southwestern part of the Oasis Valley Hydrographic Area and is generally bounded by Pahute Mesa to the north and northeast, Springdale Mountain and the Bullfrog Hills to the west, Bare Mountain to the south, Yucca Mountain to the southeast, and Timber Mountain to the east (fig. 2). The Oasis Valley discharge area is located between Oasis Mountain and Bare Mountain on the floor of Oasis Valley (fig. 3). The valley floor is typified by a gently southward-sloping terrain ranging in altitude from 3,900–4,000 ft above mean sea level at the northernmost part of the discharge area to approximately 3,200 ft at the lowermost discharge area south of Beatty. The Oasis Mountain Hogback (fig. 3), a rectangular bedrock exposure east of the Hogback Fault (fig. 4), starkly contrasts with the surrounding valley floor. The Oasis Mountain Hogback protrudes upward by as much as 400 ft, forming fairly steep volcanic-rock outcrops.

The climate in Oasis Valley is typical of many desert regions that are characterized by short mild winters, long hot summers, and low annual rainfall. Long-term climatic data specific to Oasis Valley can be inferred from information available for the National Weather Service station Beatty 8N (station



Base from U.S. Geological Survey digital data, 1:100,000, 1978-89: 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

- 🟩 **Oasis Valley discharge area**
- ■ **Other major discharge areas**—Modified after Laczniak and others (2001)
- 🟥 **Areas of underground nuclear testing**—Modified after Laczniak and others (1996)
- —··— **Death Valley Regional Flow System**—Modified from Harrill and others (1988)

Figure 1. Oasis Valley and other major areas of natural ground-water discharge within the Death Valley regional flow system, Nevada and California.

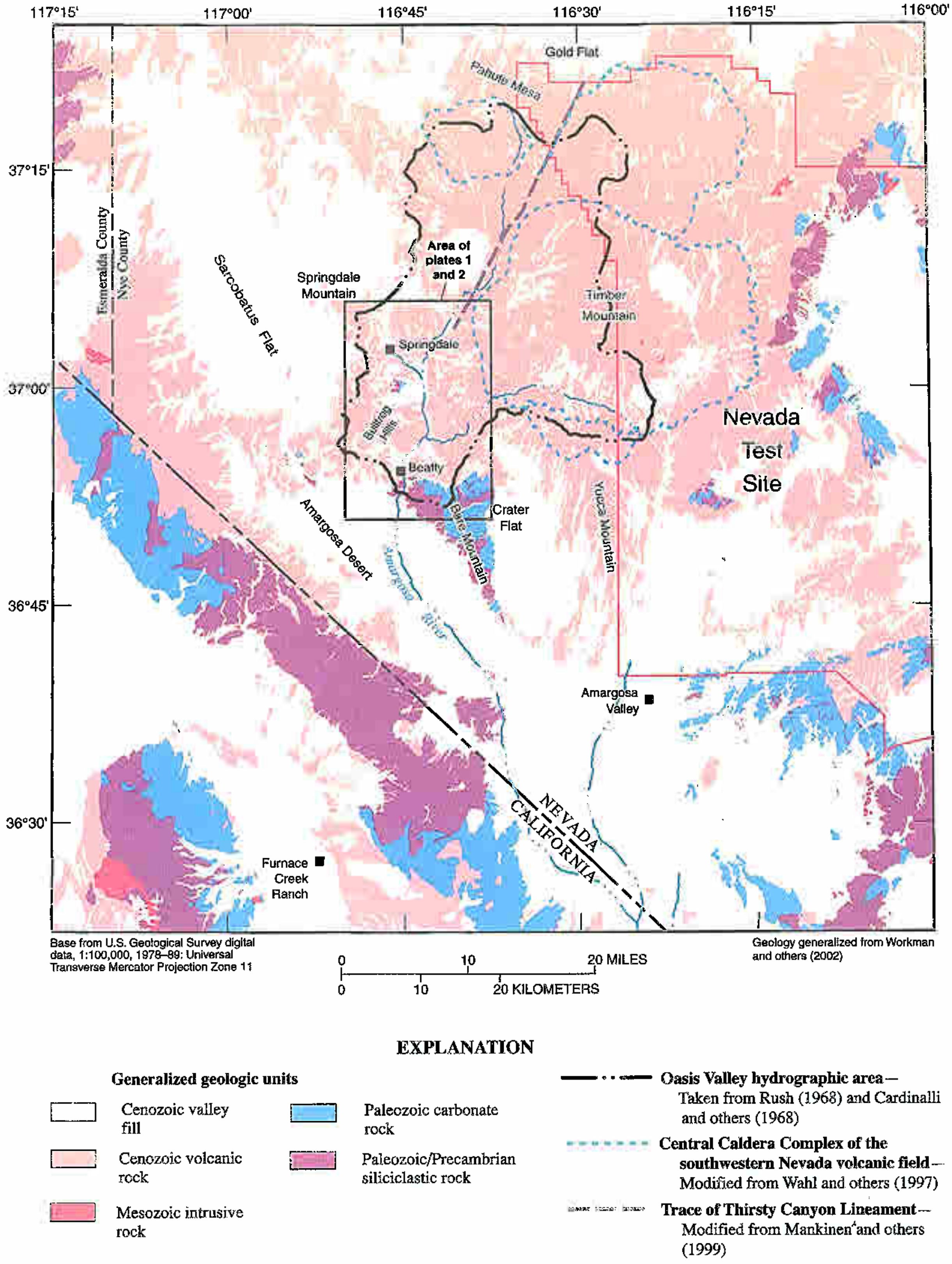
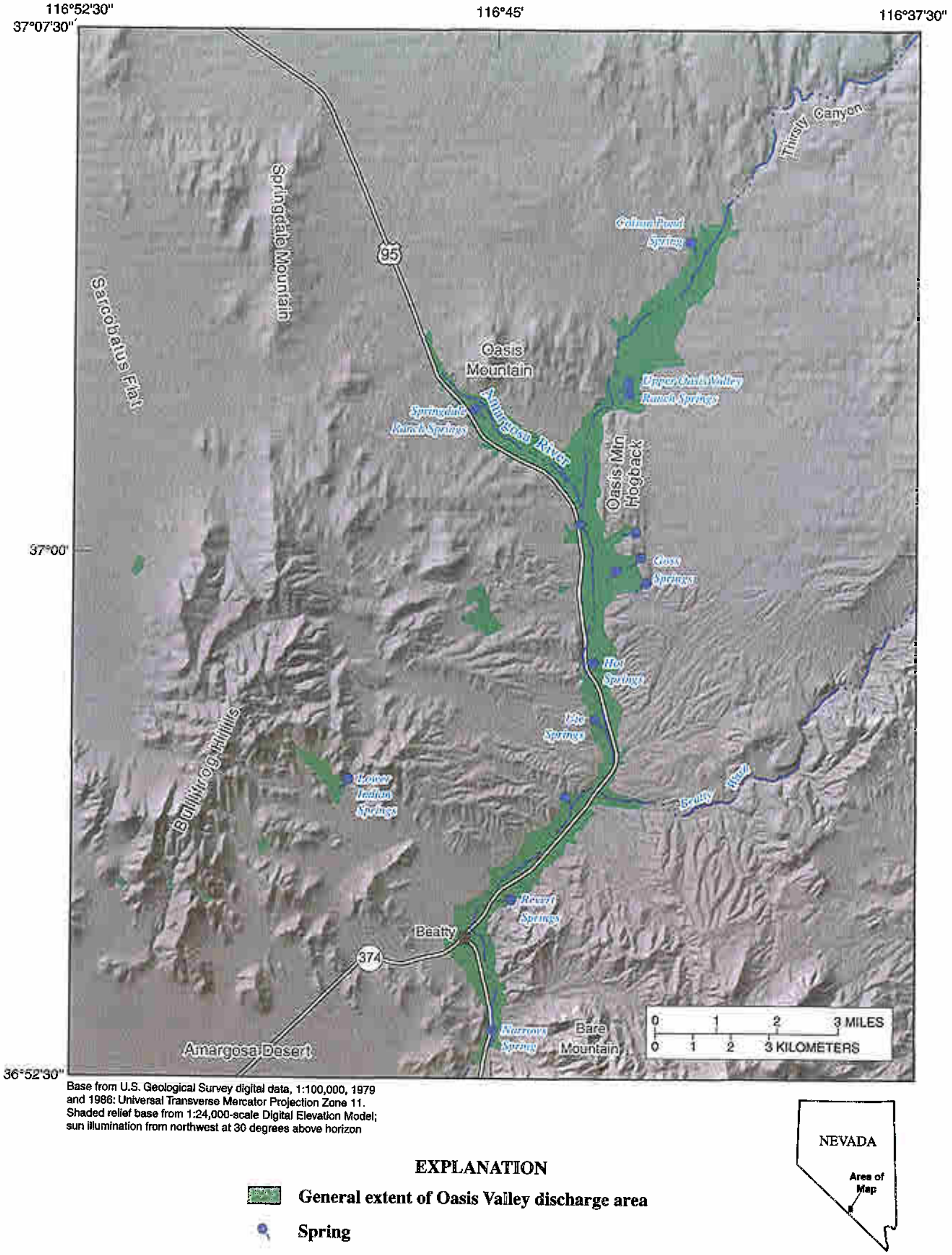


Figure 2. Generalized geology of Oasis Valley area, Nevada and California.



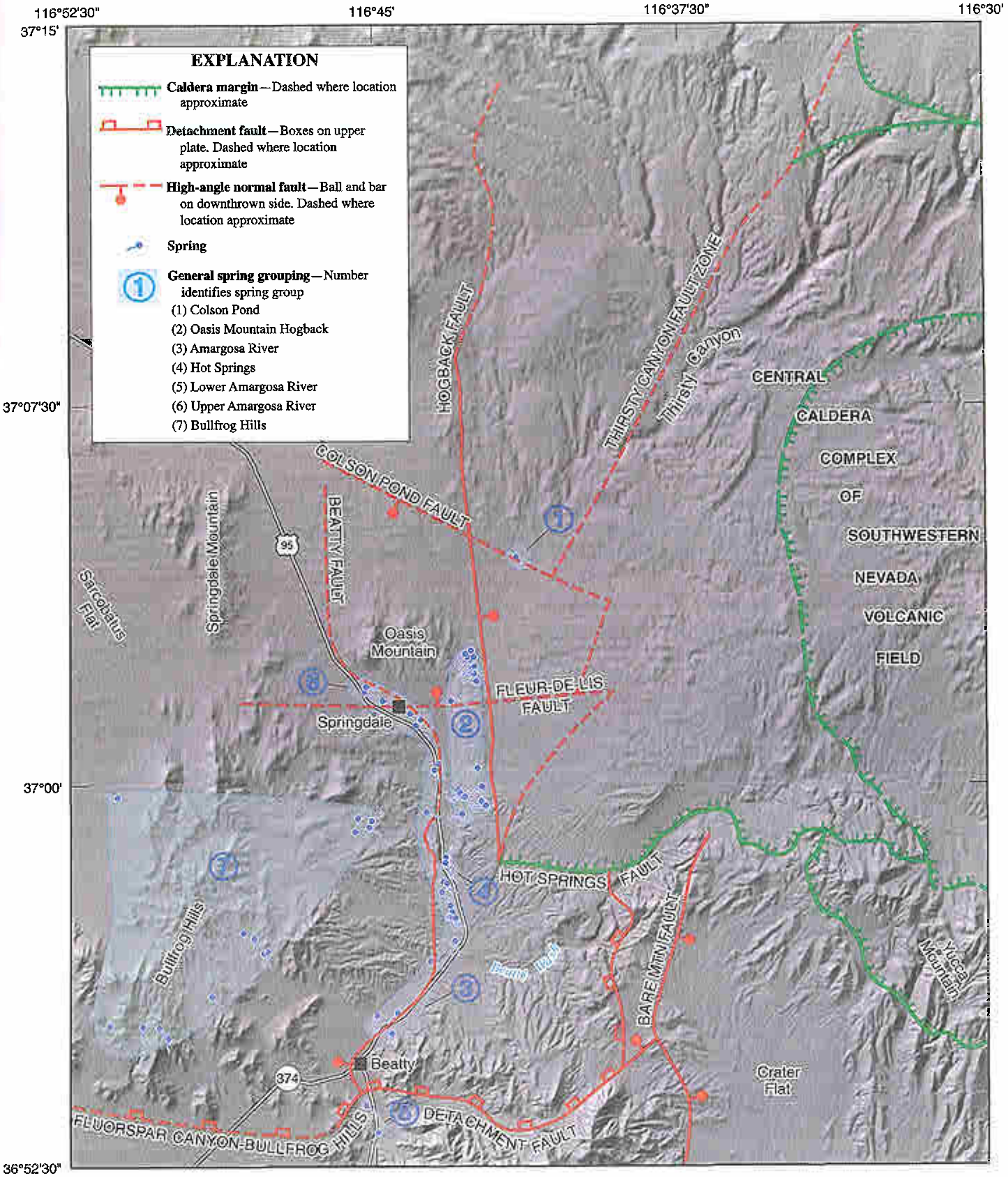
Base from U.S. Geological Survey digital data, 1:100,000, 1979 and 1986: Universal Transverse Mercator Projection Zone 11. Shaded relief base from 1:24,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

EXPLANATION

🟩 **General extent of Oasis Valley discharge area**

● **Spring**

Figure 3. Major hydrographic and physiographic features in Oasis Valley, Nevada.



Base from U.S. Geological Survey digital data, 1:100,000, 1979 and 1986: Universal Transverse Mercator Projection Zone 11. Shaded relief base from 1:24,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

Figure 4. Major structural features controlling spring discharge in Oasis Valley, Nevada.

number 260718-4) located near Beatty, Nev. (Desert Research Institute, Western Regional Climate Center, electronic data accessed at <http://www.wrcc.dri.edu/summary/climsmnv.html> on June 17, 2001) (pl. 1). Mean annual precipitation during the station's period of record (1972–2000) was 6.33 in. The maximum and minimum recorded annual precipitation was 12.62 in. in 1998 and 2.43 in. in 1989. The maximum and minimum average monthly precipitation occur in March (1.10 in.) and June (0.22 in.), respectively. Annual precipitation during this study was 5.6 in. in 1996, 6.6 in. in 1997, and 12.6 in. in 1998. Precipitation collection at the weather station was incomplete in 1999 and 2000. However, precipitation was determined to be 4.7 in. in 1999 and 6.8 in. in 2000 based upon available weather station data and supplemental rainfall data collected at multiple evapotranspiration stations in Oasis Valley.

Mean annual temperature at weather station Beatty 8N, for its period of record, was 59.0°F. The maximum and minimum annual mean temperatures were 61.2°F in 1996 and 56.6°F in 1973. Mean monthly temperatures ranged from 78.8°F in July to 41.3°F in January. Temperatures ranged between 112°F on July 7, 1989, and 2°F on December 22, 1990. Mean annual temperatures during the study were 61.2°F in 1996, 60.2°F in 1997, 57.5°F in 1998, 59.7°F in 1999, and 58.8°F in 2000. Mean annual temperature during this study was 59.5°F.

In contrast to most desert basins, Oasis Valley has a high concentration of springs (fig. 4). Structurally controlled conduits and changes in rock unit lithology and thickness produce the more than 70 springs and seeps located in Oasis Valley. Although long-term spring discharge measurements are unavailable for these springs or seeps, some periodic measurements are in Malmberg and Eakin (1962), Thordarson and Robinson (1971), White (1979), and McKinley and others (1991).

A diverse community of plants depends on water provided by the numerous springs scattered throughout Oasis Valley. This community includes many varieties of grasses, reeds, shrubs, and trees, with denser growths concentrated along spring pools and drainages. Areas influenced by spring flow include groves of desert ash, cottonwood, and desert willow; expansive meadows of saltgrass, bunchgrass, and wire grass; and open marshland of cattails, reeds, and bulrush. Sparse to moderately dense covers of greasewood, rabbitbrush, and wolfberry are found in areas peripheral to those influenced by spring flow. The densest population of trees is found in the southernmost part of Oasis Valley along the Amargosa River drainage. Upland areas not influenced by spring discharge are dominated by flora more typical of the Mojave Desert, primarily sparse covers of creosote bush, saltbush, and desert holly.

The riparian and desert aquatic environments of Oasis Valley provide food and shelter to numerous birds, insects, fish, reptiles, amphibians, and mammals. Some animals benefiting from local aquatic desert and riparian habitats are Neotropical migratory birds, endemic snails, Oasis Valley speckled dace, and the Amargosa Toad. A population of wild burros also is found in the area.

Within Oasis Valley, the primary drainage is the intermittent Amargosa River (figs. 1, 2, and 3), which seldom flows through its entire extent except following infrequent storms. Short reaches of the river, directly downgradient from major springs, flow throughout the year. The length of reach flowing and the amount of flow vary during the year; longer, more continuous, and greater flows typically occur in winter. Precipitation is more likely in the winter, during which water losses through evapotranspiration are reduced by cooler temperatures and the dormancy of the vegetation. Beatty Wash and Thirsty Canyon (fig. 4), located in central and northern Oasis Valley, respectively, do not flow except during and after more intense storms. Numerous small unnamed channels, which may exhibit seasonal fluctuations in flow similar to the Amargosa River, drain many of the larger local springs and wetlands. A few impoundments near springheads and irrigation ditches have been constructed to support human activities in the area.

Hydrogeology

The many springs and a shallow water table in Oasis Valley are maintained primarily by ground water that moves into the area through a regional volcanic-rock aquifer system. This system is made up of a series of interlayered aquifers and confining units. Ground water in Oasis Valley originates in areas to the north and northeast. Its recharge area includes Pahute Mesa in the NTS (Laczniak and others, 1996). Geologic structures such as faults and caldera boundaries affect the flow path of the southward-moving ground water. Springs typically occur in these areas where ground water encounters faults.

Four major hydrogeologic units make up the regional volcanic-rock aquifer system in Oasis Valley. These units are the alluvial aquifer, nonwelded-tuff confining unit, welded-tuff aquifer, and basement confining unit. The alluvial aquifer, which overlies the volcanic units, consists primarily of valley-fill deposits and has a relatively high effective porosity and moderate matrix permeability (Fridrich and others, 1999). The valley-fill deposits typically consist of Quaternary sand, silt, clay, and gravel in the Oasis Valley discharge area and Tertiary sand and gravel in other parts of Oasis Valley. The aquifer usually is unconfined except where locally overlain by low-permeability deposits. The thickness of valley-fill deposits typically ranges from 10 to 100 ft in the Oasis Valley discharge area and exceeds 1,000 ft in the area east of the Hogback fault (fig. 4).

Throughout much of Oasis Valley, a nonwelded-tuff confining unit separates the alluvial aquifer from the underlying welded-tuff aquifer. This confining unit has fairly high matrix porosity, but low permeability (Fridrich and others, 1999), is fairly continuous, and extends laterally to the southwest from a concealed area near Pahute Mesa. The unit terminates in the south at the Hot Springs Fault and in the west at the Hogback Fault. The thickness of the nonwelded-tuff confining unit typically ranges from 100 to 1,000 ft and reaches a maximum in the area east of the Oasis Mountain Hogback (fig. 4).

The regional welded-tuff aquifer consists of numerous subhorizontal layers of Tertiary-age welded tuffs, lavas, and bedded tuffs. The welded-tuff aquifer generally has low effective porosity and moderate fracture permeability (Fridrich and others, 1999); however, the permeability of the intra-unit layers varies. The aquifer typically is confined either by the overlying non-welded tuff confining unit or by the low-permeability intra-unit layers (Fridrich and others, 1999). The thickness of the welded-tuff aquifer decreases south and west from the southwestern Nevada volcanic field (SWNVF) toward Oasis Valley (fig. 4). Welded-tuff aquifer thickness, according to gravity data from Hildenbrand and others (1999), averages about 10,000 ft within the SWNVF central caldera complex, about 5,000 ft in the area between the central caldera complex and the eastern edge of the Oasis Valley discharge area, about 2,500 ft beneath the discharge area, and less than 1,600 ft west of the discharge area, and thins to extinction at the southern end of Oasis Valley.

Paleozoic sedimentary rocks and Miocene intrusive rocks underlie the welded-tuff aquifer and form the basement confining unit beneath Oasis Valley. This very-low-permeability confining unit may locally include some high-permeability carbonate rocks. Within this unit, the carbonate rocks are subordinate to the very-low-permeability clastic rocks and granitoids and lack the continuity to host any substantial regional ground-water flow (Fridrich and others, 1999).

Geologic structures found throughout the area act both as conduits and barriers to ground-water flow. These geologic structures include, but are not limited to, faults and caldera boundaries. Conduits generated by these geologic structures often create preferred pathways, typically along the strike or at the intersections of multiple faults, where permeability is enhanced by faulting. Barriers typically are perpendicular to strike and most often are caused by juxtaposition of less-permeable against more permeable rock or by low permeability associated with fault gouge (Fridrich and others, 1999). Major geologic structures in Oasis Valley (fig. 4) most likely to influence ground-water flow are (1) the Thirsty Canyon fault zone, a northeast-striking fault zone/lineament, (2) the north-striking Hogback, Bare Mountain, and Beatty faults, (3) the east-west striking Colson Pond, Fleur-de-Lis, and Hot Spring faults, and (4) the Fluorspar Canyon–Bullfrog Hills detachment fault.

Hydraulic gradients based on regional water-level data indicate that ground water discharging at Oasis Valley originates from areas to the north and northeast of the valley (Laczniak and others, 1996). Precipitation on local highlands and subsurface flow from areas to the north are primary sources of discharged water. Recharge occurs at higher elevations in western Pahute Mesa, Timber Mountain, the Bullfrog Hills, and Bare Mountain (figs. 1 and 3). Only a minimal amount of ground water flows into Oasis Valley from the west (Malmberg and Eakin, 1962). The water table between upland recharge areas and the Oasis Valley discharge area typically is several hundred to several thousand feet below the land surface (Malmberg and Eakin, 1962).

Most of the ground water flowing south-southwestward into Oasis Valley through the welded-tuff aquifer is diverted upward along faults (fig. 5). These diversions are a consequence of enhanced permeability along faults, contrasts in water-transmitting properties caused by the juxtaposing of hydrogeologic units along faults, a general thinning of the welded-tuff aquifer

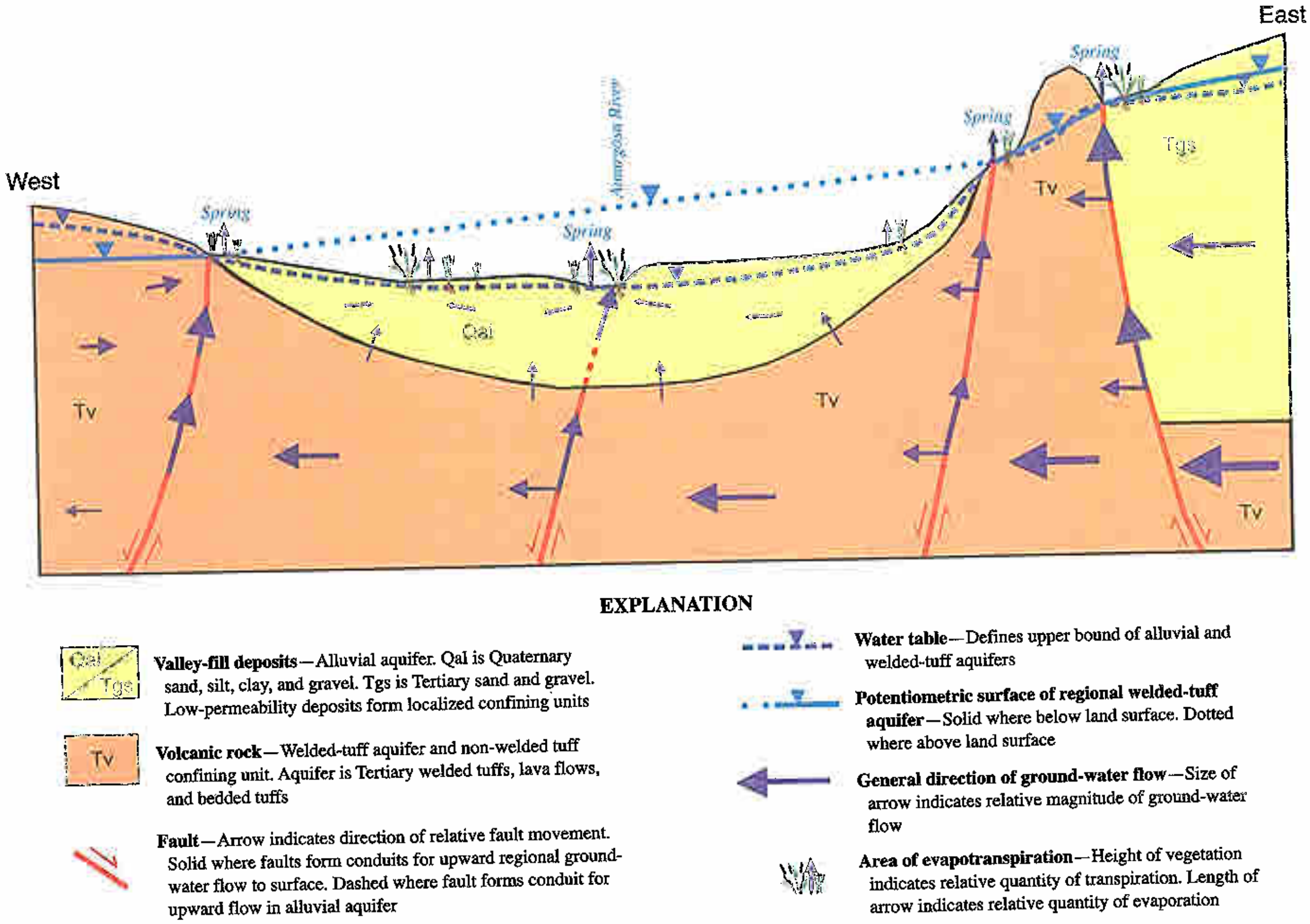


Figure 5. Generalized cross-section showing local hydrographic and geologic features controlling ground-water flow and discharge in Oasis Valley, Nevada.

approaching Oasis Valley, and the termination of the welded-tuff aquifer against nearly impermeable siliciclastic rock at the southern end of Oasis Valley.

Springs occur throughout Oasis Valley where upward diversions coincide with areas in which the potentiometric surface is above land surface. Ground water entering Oasis Valley through the welded-tuff aquifer that is not discharged as springflow either flows upward and recharges the valley-fill deposits, is withdrawn for human uses, or flows laterally out of the valley as subsurface outflow. The most likely pathway for this subsurface outflow is to the south through the alluvium-filled Amargosa River channel into the Amargosa Desert. Other potential but less likely pathways for subsurface outflow are to the southeast under a ridge separating Oasis Valley and Crater Flat (fig. 4) (Fridrich and others, 1999) and to the south from the Bullfrog Hills into the Amargosa Desert (fig. 3).

About 75 springs and seeps are mapped throughout Oasis Valley. Flow rates range from less than 1 gal/min to more than 200 gal/min. Water temperatures range from about 60°F to more than 100°F (White, 1979; McKinley and others, 1991). Although flow and temperature characteristics vary, most of the springs in Oasis Valley can be grouped according to their hydrogeologic setting (fig. 4):

(1) Colson Pond group: Includes springs located along the Colson Pond fault. These springs probably form as a result of a transmissivity change across the Colson Pond fault. Their likely source is water flowing from the north and northeast beneath Pahute Mesa.

(2) Oasis Mountain Hogback group: Includes springs located west of the Hogback fault. These springs probably form as a result of an abrupt westward thinning of the welded-tuff aquifer across the Hogback fault. Their likely source is water flowing from Pahute Mesa.

(3) Amargosa River group: Includes springs along the Amargosa River north of Beatty. These springs probably form as a result of a transmissivity change and a disruption in aquifer continuity across the Beatty fault. Their likely source is a mixture of the water flowing into Oasis Valley from the east, west, and north.

(4) The Hot Springs group: Includes springs located in the central part of the Oasis Valley discharge area along the east-west-striking Hot Springs fault. Elevated water temperatures of about 105°F indicate probable upward flow along the fault from deeper parts of the flow system. Their likely source is flow from the east and north, possibly Timber Mountain and/or Pahute Mesa.

(5) Lower Amargosa River group: Includes springs issuing from channel-fill deposits along the Amargosa River south of Beatty. Their primary source probably is water flowing from the north through Oasis Valley.

(6) Upper Amargosa River group: Includes springs located in the northwest fork of the Oasis Valley discharge area. These springs probably form as a result of a transmissivity change and disruption in aquifer continuity across the Beatty fault. Their likely source is inflow from the north and northwest (White, 1979).

(7) Bullfrog Hills group: Includes springs located west of the Amargosa River channel. These springs probably form as a result of permeability changes within the welded-tuff aquifer caused by hydrothermal alteration. Their likely source is local recharge to nearby highlands.

GROUND-WATER DISCHARGE

Ground water discharges in or leaves Oasis Valley by means of five major processes: (1) springflow, (2) transpiration by local vegetation, (3) evaporation from soil and open water, (4) subsurface outflow, and (5) withdrawal for local water uses. Of the four natural processes, springflow is the most visible form of discharge. As ground water emerges from the many springs and seeps scattered about Oasis Valley, it either is captured in local marshes and small pools or is channeled into free-flowing drainages. Once at the surface, water evaporates to the atmosphere or infiltrates valley-fill deposits. Little surface water flows out of Oasis Valley except during short periods (lasting less than a month) that follow occasional, intense rainstorms (U.S. Geological Survey, 1993–95).

Most of the spring and surface flow that is not evapotranspired infiltrates the valley-fill deposits and recharges the alluvial aquifer (fig. 5). In addition to this recharge, the alluvial aquifer is recharged from below by diffuse or fault-associated upward flow from the welded-tuff aquifer. Other than the occasional influx of water from rainfall or surface inflow into the valley-fill deposits, these two sources provide most of the recharge maintaining the alluvial aquifer. Although data are limited, rainfall or surface inflow from areas outside the borders of the valley-fill deposits most likely is evaporated before it can recharge the shallow ground-water system, thus it is considered of lesser importance.

Water stored locally within the alluvial aquifer in areas in which the water table is at or near land surface becomes available for use by plants. Evapotranspiration (ET) is a composite term for two processes: (1) the evaporation of water from bare soil or from bodies of surface water, and (2) transpiration, a biological function of plants in which water is released to the atmosphere through the stomata of plant tissue. ET is the primary process by which ground water is removed from the alluvial aquifer. Seasonal changes in ET may be responsible for seasonal fluctuations in the local water table — generally observed as a declining water table in the summer and fall, and a rising water table in the winter and spring (Laczniak and others, 1999).

Some portion of natural ground-water discharge leaves Oasis Valley as subsurface outflow. This ground water flows through a narrow veneer of the valley-fill alluvium at the southernmost extent of Oasis Valley into adjacent valley-fill deposits in the Amargosa Desert. An additional quantity of ground water is withdrawn from wells and springs in Oasis Valley to satisfy local water supply requirements.

Evapotranspiration

One method of estimating the natural loss of ground water from Oasis Valley is to estimate the ET from areas of ground-water discharge. An estimate of ET includes water losses from the regional welded-tuff aquifer both by diffuse or preferential, fault-associated upward flow into the alluvial aquifer and by spring and seep flow. The ET estimate includes most spring and seep flow because this water either evaporates or infiltrates the subsurface, recharging the alluvial aquifer where it eventually evapotranspires or leaves Oasis Valley by other discharge processes.

As part of their reconnaissance study of Oasis Valley, Malmberg and Eakin (1962) estimated annual ET to be 2,000 acre-ft. They calculated annual ET as the product of the acreage and the average ET rate of local phreatophytes. Based on studies by W.A. Beetem and R.A. Young, Blankennagel and Weir (1973, p. 21) reported that annual ground-water discharge from Oasis Valley might exceed the Malmberg and Eakin (1962) estimate by a factor of two or more. This discrepancy, combined with results from recent studies (Johnson, 1993; Nichols and others, 1997; Laczniak and others, 1999) suggesting that ET rates for local phreatophytes may be higher than those used by Malmberg and Eakin (1962, p. 25), provided the basis for initiating a study to re-evaluate and more rigorously quantify ET and other ground-water discharge in Oasis Valley. An improved quantification of ground-water discharge would significantly help in formulating an understanding of ground-water flow and aid ongoing development of a flow model for the Death Valley regional ground-water flow system.

The method used to quantify ET from Oasis Valley follows an approach similar to that used by Laczniak and others (1999) to estimate ET from the nearby Ash Meadows discharge area (fig. 1). The approach assumes that total ET can be quantified by summing estimates of annual ET computed for areas of similar plant cover (in terms of type and density) and soil cover (in terms of type and moisture content). These areas of similar vegetation and soil cover hereafter are referred to as ET units. Annual ET from each ET unit is computed as the product of the unit's acreage and ET rate.

The major difference between the Malmberg and Eakin (1962) method and the approach used in this study is the set of specific techniques used to identify the major ET units, determine their spatial distribution, and estimate their associated ET rates. Malmberg and Eakin identified and delineated one generalized ET unit from vegetation and soil maps that were constructed using standard field techniques, and estimated an ET rate for this unit from rates determined for similar phreatophytes growing elsewhere in the southwestern United States (Lee, 1912; Robinson, 1958; White, 1932; Young and Blaney, 1942). The technique used in this study refines their approach by incorporating satellite imagery and remote-sensing techniques to better delineate and discriminate ET units, and by determining ET rates for each ET unit using long-term micrometeorological data collected at numerous sites within the Oasis Valley and nearby Ash Meadows discharge areas. In addition, because local vegetation and soil-moisture conditions are largely a consequence of the availability of ground water, water levels were measured to define the depth and seasonal fluctuation of the water table.

Evapotranspiration Units

ET units were identified and mapped in Oasis Valley through a procedure by which spatial changes in vegetation and soil covers were determined from remotely sensed spectral reflectance data. The procedure discriminates ET units on the basis of spectral similarities identified from Landsat Thematic Mapper (TM) imagery for major vegetation and soil covers within the Oasis Valley discharge area.

Thematic Mapper Imagery

TM imagery is acquired by satellites equipped with sensors that measure reflected solar and emitted radiation from the Earth's surface and that scattered from the atmosphere. Measurements are made within seven wavelength bands spanning discrete parts of the visible and infrared regions of the electromagnetic spectrum. Each band is referred to as a TM channel. Six TM channels (1, 2, 3, 4, 5, and 7) measure reflected solar radiation in the visible through short-wave infrared regions (fig. 6). A seventh band, channel 6, which measures thermal energy radiated by the Earth, was not used in this study.

Spectral data received by satellite sensors are transmitted to earth as digital numbers, each denoting the reflectance of the wavelengths across each of the TM channels from a small area of the earth's surface (fig. 6). The surface area scanned by the sensor for TM channels 1, 2, 3, 4, 5, and 7 measures about 100 ft by 100 ft. Each square-shaped area is referred to as a picture element, or *pixel*; the dimensions of each pixel define the spatial resolution of the imagery. One basic advantage of these digital data is that they can be mathematically manipulated, processed, and analyzed.

Satellite data have long been used to identify and delineate different land covers (Anderson and others, 1976, p. 2; American Society of Photogrammetry, 1983, p. 23–25). Vegetation, water, and soil covers have distinct spectral properties and can be identified by characteristic patterns or signatures defined by their spectral-response curves (fig. 6). A detailed analysis of

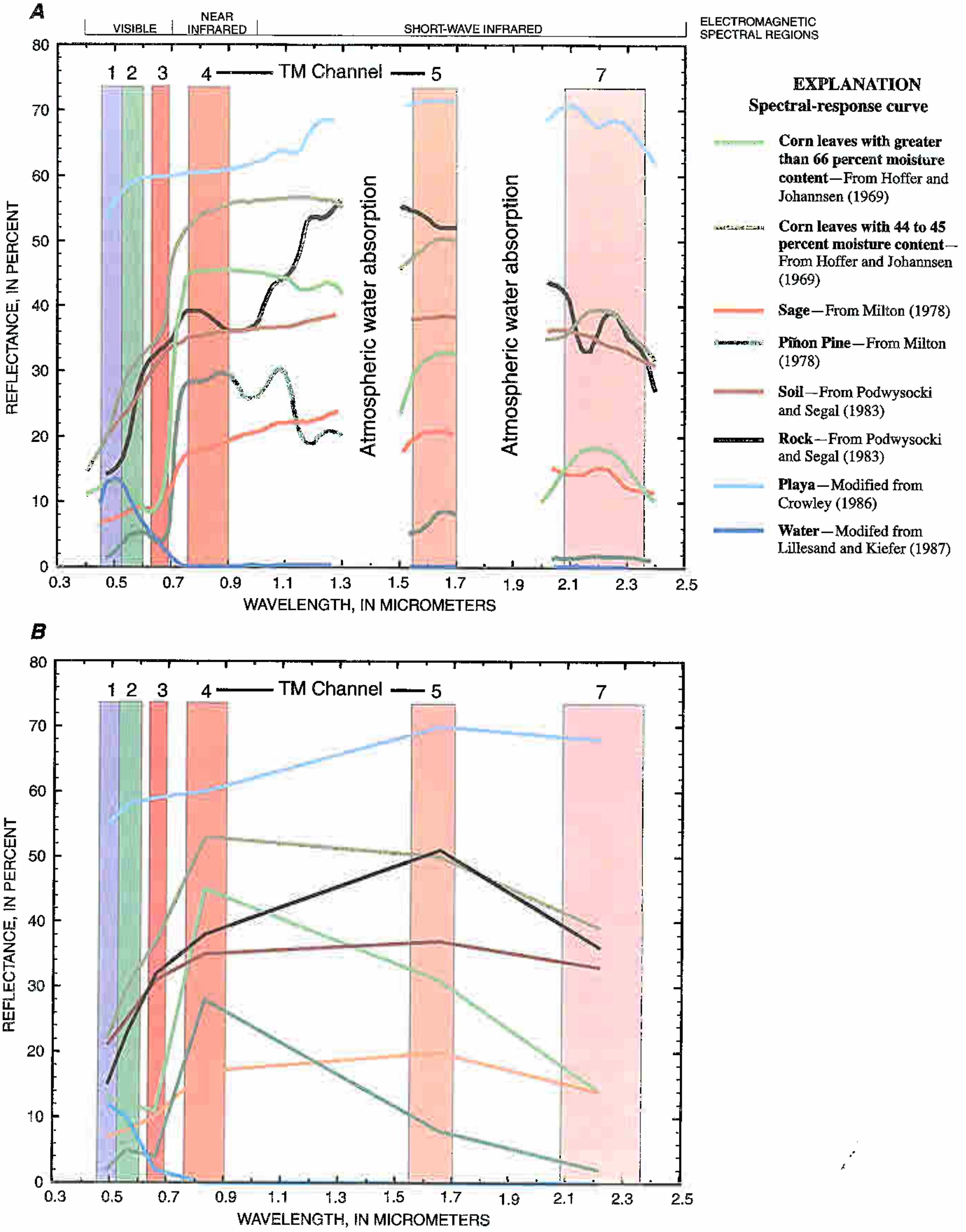


Figure 6. Spectral-response curves for land covers of different vegetation, soil, and moisture conditions: (*A*) Continuous field or laboratory measured reflectance, and (*B*) reflectance developed for thematic mapper channels 1, 2, 3, 4, 5, and 7 from measured curves.

the shape, slope, and absorption features within a land cover's spectral-response curve often can be used to identify differences in vegetation type, density, and health, as well as differences in soil type and moisture content (Goetz and others, 1983, p. 576–581). Past studies have shown that ET rates throughout the Great Basin region vary with vegetation and soil covers—in general, the denser and healthier the vegetation or the wetter the soil, the greater the rate of evapotranspiration (Ustin, 1992; Laczniak and others, 1999; Nichols, 2001). The procedure used to identify and map ET units in Oasis Valley takes advantage of this relation and the characteristic pat-terns in the spectral response of differing vegetation and soil covers, particularly those associated with the evapotranspiration of ground water.

Classification

The process of identifying pixels on the basis of patterns in their reflectance spectra is referred to as a classification. If pixels are grouped to represent specific land covers, the classification is called a land-cover classification, and, if grouped to discriminate vegetation, is referred to as a vegetation classification. Whatever the classification type, each different group defines a specific class. The procedure presented here ultimately groups pixels into unique ET units, and is referred to as an ET-unit classification.

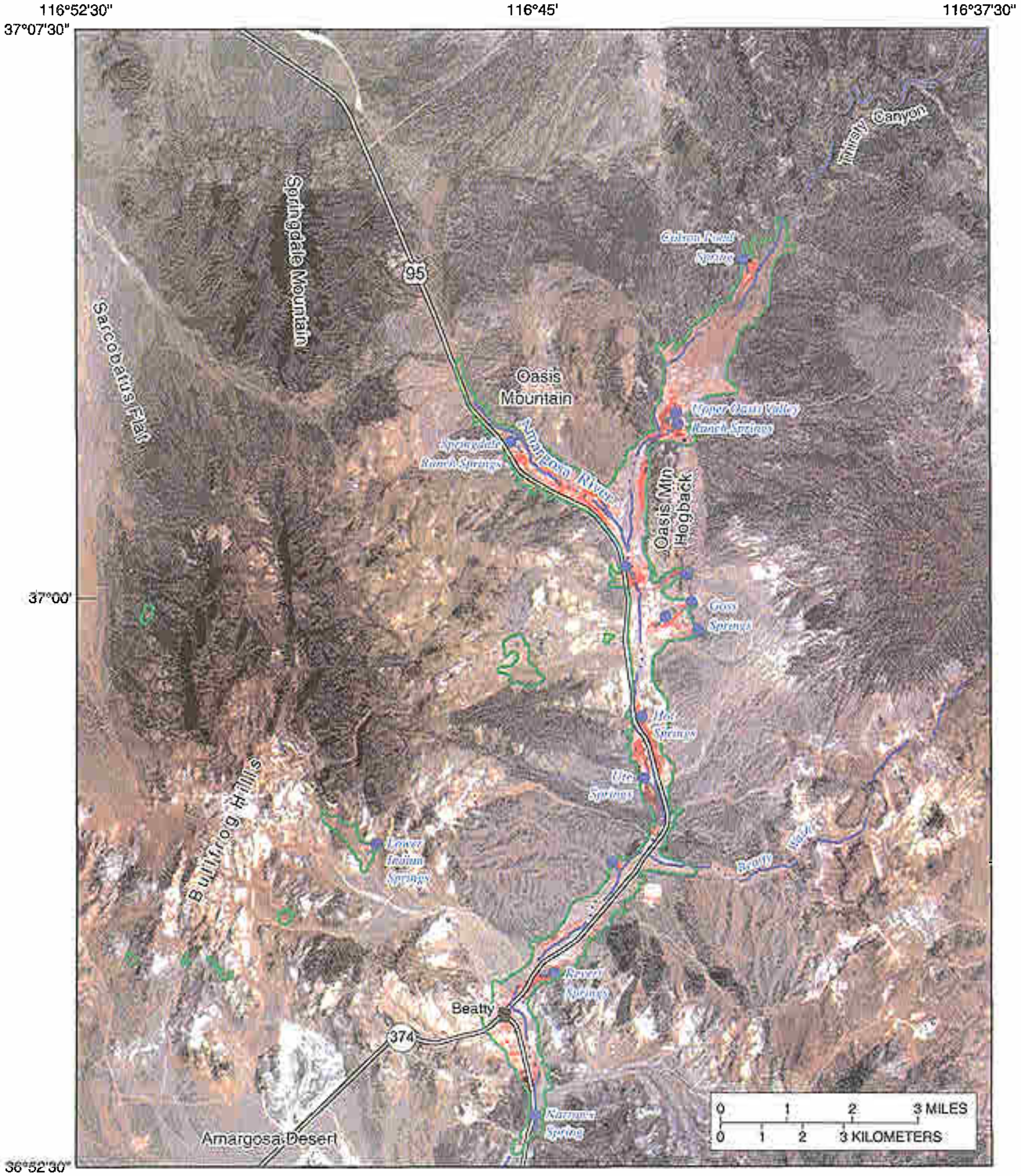
The TM data used to classify ET units within the Oasis Valley area was imaged June 13, 1992 (scene identification number LT5040035009216510, fig. 7). The decision to use June 1992 imagery was based on (1) June being a period of high vegetation vigor, (2) 1992 having slightly above-normal precipitation, and (3) the desire for consistency with other recent studies of ET from discharge areas in the Death Valley regional flow system (Laczniak and others, 1999, 2001). Although the procedure used here is similar to that used by Laczniak and others (1999) in the Ash Meadows discharge area, it differs in the number of images and image dates used by the classification process. Laczniak and others (1999) used two TM images, one acquired in June 1992 and the other in September 1992; this study used only the June image. The June imagery was used to represent conditions of near-maximum plant vigor and high moisture and the September imagery to represent conditions of high plant stress (dormancy) and low moisture. Results and insights gained from the Ash Meadows study indicated that a single-date classification would be adequate for discriminating ET units. The imagery was corrected for atmospheric effects using the method described by Chavez (1989).

The first step in the overall procedure reduced the number of pixels used to develop spectral statistics by constraining the area of interest to that of the discharge area (pl. 1). The outer extent of the discharge area was defined using a modified soil-adjusted vegetation index (MSAVI; Qi and others, 1994) developed from the June imagery. The MSAVI uses TM channels 3 and 4 to compute a vegetation index that increases the dynamic range of the vegetation signal by minimizing background influences from the soil. This outer boundary was refined based on information gathered during numerous field visits early in the study. Only pixels within this boundary were classified during the processing.

The classification procedure first identified the different spectral signatures present within the discharge area. The different spectral signatures present within the TM imagery were identified using an unsupervised approach (Lillesand and Kiefer, 1987). This approach identified 188 spectral signatures on the basis of statistical similarities between reflectance values in TM channels 1, 2, 3, 4, 5, and 7. Each signature defined a unique spectral-response curve characterized by statistical variables representing a different set of reflectance values. An example illustrating differences in the spectral signatures of different vegetation and soil covers and their associated response curves as convolved over TM channels 1, 2, 3, 4, 5, and 7 is shown in figure 6.

Next, the procedure associated each pixel within the imagery to one of the identified spectral-response curves. This association was made using the maximum likelihood classification technique (Lillesand and Kiefer, 1987, p. 685–689). This technique compares reflectance values of each pixel against those defining each of the unique spectral-response curves to calculate the statistical probability of a pixel being represented adequately by a spectral-response curve. The procedure assigns each pixel to the spectral-response curve having the greatest statistical probability.

The next step in the procedure was to group spectral-response curves into clusters that best represent the ET units within the discharge area. Each group is referred to as a spectral cluster and can be discriminated by the differences in the characteristic shape defined by the slope and amplitude of the cluster's spectral-reflectance curves. These different shapes



Base from U.S. Geological Survey digital data, 1:100,000, 1979
and 1986: Universal Transverse Mercator Projection Zone 11

EXPLANATION

— **General Extent of Oasis Valley Discharge Area**

● **Spring**

Figure 7. Color-infrared composite generated from bands 4, 3, and 2 (red, green, and blue, respectively) of June 13, 1992, thematic mapper image, Oasis Valley, Nevada (scene identification number LT5040035009216510).

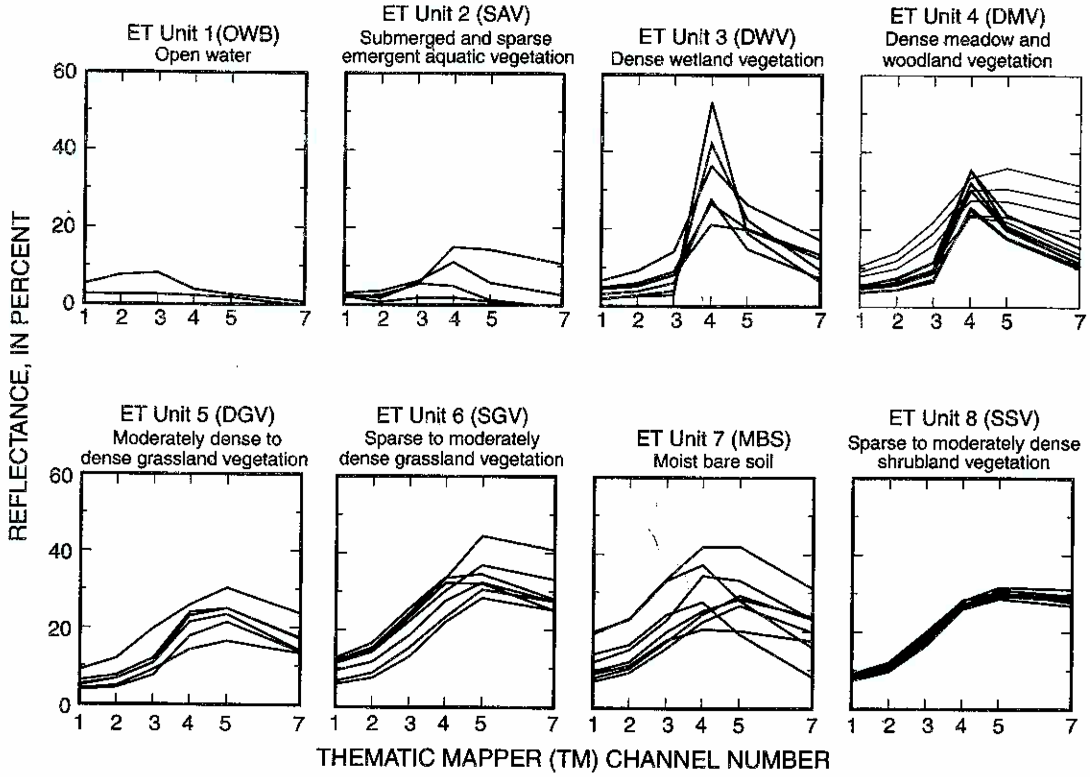


Figure 8. Spectral clusters and component spectral-response curves used for classifying ET units in Oasis Valley discharge area, Nevada. Text in parentheses is ET-unit identifier.

result primarily from differences in the amount of spectral absorption and scatter over a particular TM channel.

Spectral-response curves initially were grouped into the seven ET units similar to those delineating areas of ET in the Ash Meadows area (Laczniak and others, 1999, table 3). The placement and groupings of spectral curves were done on the basis of similarities in the statistics defining their reflectance values and on similarities in vegetation and soil conditions noted in the field. Field observations made during many visits to identify actual vegetation and soil conditions within pixels resulted in significant modifications of the groupings initially made based solely on similarities in reflectance values. Ultimately, this dual approach grouped about 130 of the unique spectral signatures into 8 clusters (fig. 8) representing the different vegetation and soil conditions consistent with areas of ground-water ET in Oasis Valley. The 8 clusters given in figure 8 include one additional cluster to those given by Laczniak and others (1999, table 3) for Ash Meadows. This added cluster was included to account for sparse to moderately dense shrubland vegetation not present in the Ash Meadows area. These shrubland communities are dominated by greasewood, rabbitbrush, wolfberry, or some combination thereof (table 1). The eight clusters identify the different ET units within those areas of Oasis Valley dominated by open water, phreatophytes, and moist bare soil (table 1). The remaining 60 or so spectral signatures were associated with pixels falling in areas dominated by sparse upland desert vegetation or in more xeric habitats and were used to discriminate those areas of no substantial ground-water ET. The spectral cluster for this ET unit is inclusive of a variety of spectral-response curves having no identifiable characteristic pattern.

Most spectral-response curves included within a cluster exhibit a similar characteristic shape (fig. 8). The two primary exceptions are the clusters representing ET units 4 (dense meadow and woodland vegetation) and 7 (moist bare soil). Each of these clusters contains spectral-response curves exhibiting two or more distinct characteristic shapes. These multiple patterns result from the inclusion of more than one vegetation or soil type within the cluster. For example, ET unit 4 includes both dense grasses and trees, each

Table 1. Evapotranspiration (ET) units determined from spectral analysis of satellite imagery data, Oasis Valley discharge area, Nevada, June 1992

[Symbol: —, non-applicable.]

ET-unit identifier	ET-unit number	ET-unit area (acres)	General description of ET unit [1]
UCL	0	—	Area of no substantial ET from ground-water source (unclassified); water table typically greater than 20 feet below land surface; soil very dry
OWB	1	1	Area of open water, primarily spring pool or pond
SAV	2	4	Area of submerged and sparse emergent aquatic vegetation; includes primarily shallow part of open water areas; perennially flooded; water at surface
DWV	3	40	Area dominated by dense wetland vegetation, primarily tall reedy and rushy marsh plants, typically tule, cattail, or giant reed; perennially flooded; water at surface
DMV	4	832	Area dominated by dense meadow and woodland vegetation, primarily trees, meadow and marsh grasses, or mixed trees, shrubs, and grasses; trees include desert ash and cottonwood, with some desert willow and mesquite; water table typically ranges from above land surface to about 20 feet below land surface; soil wet to dry
DGV	5	340	Area dominated by moderately dense to dense grassland vegetation, primarily saltgrass, and/or short rushes with an occasional tree or shrub; intermittently flooded; water table typically less than 10 feet below land surface; soil wet to moist
SGV	6	1,215	Area dominated by sparse to moderately dense grassland vegetation, primarily salt and bunch grasses with occasional tree or shrub; water table typically ranges from a few feet below land surface to about 10 feet below land surface; soil damp to dry
MBS	7	102	Area dominated by moist bare soil; vegetation very sparse, primarily grasses; intermittently flooded, water table typically near land surface throughout most of the year but in some areas declines to a maximum depth of about 5 feet below land surface during late summer and early fall; soil wet to moist
SSV	8	892	Area dominated by sparse to moderately dense shrubland vegetation, primarily greasewood, rabbitbrush, and wolfberry; water table typically ranges from about 5 feet below land surface to about 20 feet below land surface; soil damp to dry

[1] Vegetation cover descriptors: very sparse, less than 5 percent; sparse, 5 to 20 percent; moderate, 20 to 75 percent; and dense, greater than 75 percent. Soil moisture descriptors presented in relative terms. Sources for depth to water information are U.S. Geological Survey National Water Information System (retrieved June 2000), Laczniak and others (1999), and depth-to-water measurements made during the study.

of which exhibits a different spectral response (fig. 8). Both spectral responses are included in the cluster because their ET rates are assumed to be similar based on vegetation density. In the case of ET unit 7, its cluster includes multiple soil types usually distinguished by color or wetness. Although spectral responses associated with these soil types vary, they were grouped into one cluster based on the assumption that ET rates are similar.

The final step in the classification procedure was to digitally associate each pixel with an ET unit by assigning a number to each pixel. All pixels outside the boundary of the discharge area and those pixels within the discharge area associated with an area of no substantial ground-water ET were assigned a value of zero. The remaining pixels were assigned a value of 1 through 8 in accordance with their associated ET unit. This process created a raster image of classified ET units. The image was resampled to a finer resolution (60 ft by 60 ft) for consistency with results presented for other major discharge areas in the Death Valley regional flow system (Laczniak and others, 1999, 2001). Lastly, the image was filtered to remove spuriously and anonymously classified pixels. Filtering was performed only on those classes representing ET units 6, 7, and 8 (sparse to moderately dense grassland, moist bare soil, and sparse to moderately dense shrubland, respectively). The filtering process replaced spuriously classified pixels (areas of a few pixels or less) and filled single-pixel gaps by assigning them to the ET unit of their nearest neighbors. This process resulted in a change of less than 3 percent within any of the classified ET units.

The acreage of each ET unit, as computed from the filtered raster image, is listed in table 1. Total ET unit acreage for the Oasis Valley is 3,426 acres (table 1). About 35 percent of this acreage is sparse to moderately dense grassland (SGV) and 26 percent is

We have [illegible]
performed a classification of sites with the different ET areas.

sparse to moderately dense shrubland (SSV). Denser vegetation types, including dense meadow and woodland vegetation (DMV), moderately dense to dense grassland vegetation (DGV), and dense wetland vegetation (DWV), make up about 35 percent of the total area. Wetter ET units, open water (OWB), submerged and sparse emergent aquatic vegetation (SAV), dense wetland vegetation (DWV), and moist bare soil (MBS), make up less than 5 percent of the total area.

Some difficulty was encountered trying to discriminate between the two grassland ET units, sparse to moderately dense grassland (SGV) and moderately dense to dense grassland (DGV). Laczniak and others (2001, fig. 6 and table 1) also classified two grassland units in the Oasis Valley discharge area but described them as sparse grassland and dense to moderately dense grassland. The major difference between these grassland classifications is in the placement of two spectral-response curves representing a moderately dense grassland cover (fig. 8). Laczniak and others (2001, fig. 6) placed these curves in the cluster representing the denser grassland unit (DGV, ET unit 5, fig. 8). Their placement relied primarily on a single field visit and groupings developed during the Ash Meadows study (Laczniak and others, 1999). After numerous field visits to Oasis Valley were made throughout a 2-year period, the placement of these two curves was deemed most appropriate within the sparser grassland cluster (SGV, ET unit 6, fig. 8). Including these curves in the denser grassland cluster greatly underestimated the sparse grassland acreage observed in Oasis Valley while overestimating that of dense grassland. Placing these curves in the sparser grassland ET unit accounts for a major part of the difference between sparser grassland acreage computed for Oasis Valley by the two studies (1,215 acres by this study, table 1; and 962 acres by Laczniak and others, 2001, table 2).

Another matter of difficulty in the classification was differentiating between the moderately dense to dense grassland (DGV, ET unit 5) and moist bare soil (MBS, ET unit 7) classes. This difficulty is illustrated by similarities in the spectral-response curves within their two respective clusters (clusters 5 and 7, fig. 8). Both ET units have similar soil-moisture characteristics with the primary difference being their vegetation density. The lower density vegetation curves included in the cluster representing ET unit 5 (DGV) are similar to curves included in ET unit 7 (MBS). The somewhat large variation in shape of these curves is attributed to spectral differences resulting from mineralogical differences in the different soil covers. The placement of the more similar curves was determined primarily by conditions observed in the field. Considering the relatively low acreages covered by these two ET units (340 acres by ET unit 5 and 102 acres by ET unit 7) any error in classification would result in a minimal error in the calculation of annual ET.

Total ET unit acreage estimated by Laczniak and others (2001, table 2) was 3,473 acres compared with 3,426 acres estimated in this study (table 1). The small difference in total acreage and other minor differences in ET unit acreage between these two studies are attributed to the more rigorous association of spectral curves and observed field conditions and the filtering method applied in this study. The 3,426 acres classified in this study compares reasonably well with the 3,800 acres of phreatophytes estimated by Malmberg and Eakin (1962, p. 25). The differences in acreage between these two studies could be the result of vegetation changes stemming from increased development, increased local pumpage, or a changing climate but more likely result from differences in delineation methods.

Accuracy Assessment

The ET units, as defined and delineated, are not intended to be exact but rather to serve as generalizations of the long-term average vegetation and soil conditions within the discharge area. The accuracy of the final ET-unit classification is difficult to assess because vegetation and soil conditions throughout the Oasis Valley area are not homogeneous, and transitions from one condition to another are not abrupt but rather gradual, often occurring over broad zones. Another factor contributing to the difficulty in assessing the accuracy of mapped ET units is that vegetation and soil conditions can change during the year and from one year to the next. Despite these complications, the accuracy of the classification was assessed.

The overall performance or accuracy of a classification procedure can be described in terms of the percentage of sites correctly classified (Lillesand and Kiefer, 1987, p. 692–694). A correctly classified site is one in which the same ET unit is assigned both through field observation and by the classification procedure. The accuracy of the classification was assessed by evaluating 58 sites. Selected sites typically were within an area of 6 or more pixels of the same ET unit to provide an aerially more consistent depiction of vegetation and soil conditions. Areas used to develop the relations between spectral signatures and ET units were avoided. Access also played a major role in the selection of sites, in that much of the discharge area is in private ownership. Sites were selected to place more emphasis on the ET units having the greatest acreage. Each ET unit was represented by at least one site. Sites instrumented to collect micrometeorological data used to compute ET rates (pl. 1) in Oasis Valley were included in the assessment. Field observations included a minimum of one visit to examine and document site conditions. Each site was described, photographed, and later evaluated and assigned independently by two individuals to one of the eight ET units. The few discrepancies in assignments were resolved through discussion and site re-visitation.

Results of the accuracy assessment are presented as an error matrix in table 2 (Story and Congalton, 1986). The overall accuracy of the classification is 88 percent (ratio of the number of sites classified correctly to the total number of sites evaluated) and the average accuracy of individual classes is 91 percent. Both of these values are above the acceptability criterion of 85 percent established by Anderson and others (1976, p. 5). Most classification errors are associated with misclassifications between UCL and the sparser vegetation units, SSV and SGV (table 2). The low performance of these two units is attributed primarily to the difficulty in spectrally discriminating upland desert from sparse vegetation. These sparser vegetation classes are similar in that they often are dominated by open desert and therefore have only limited leaf area. Any misclassifications between these three units over the entire discharge area are expected to average out. Most other classification errors can be attributed to assessment sites being located near a transitional zone that only subtly defines the boundary between the three units in question.

Evapotranspiration Rates

Evapotranspiration is a process by which water from the Earth's surface is transferred to the atmosphere. This transfer requires that water change state from a liquid to a vapor, a process that consumes energy. As a result, any change in the rate of water loss by ET is reflected by a change in energy. This relation between water loss and energy consumption is the basis for energy budget methods used to estimate ET rates.

Energy Budget Method

Energy at the surface of the earth can be expressed in terms of an energy budget that balances incoming and outgoing energy fluxes. Assuming negligible energy use by biological processes and limited storage of heat by the plant canopy, the energy budget for

Table 2. Accuracy assessment of evapotranspiration-unit classification for the Oasis Valley discharge area, Nevada

[ET units are described in table 1. Diagonal values (in **boldface**) list the number of sites correctly assigned to each ET unit by spectral classification]

		Number of sites assigned by field observation									
	ET-unit identifier	**UCL**	**OWB**	**SAV**	**DWV**	**DMV**	**DGV**	**SGV**	**MBS**	**SSV**	**Total**
Number of sites assigned by spectral classification	UCL	**3**	0	0	0	0	0	1	0	2	6
	OWB	0	**1**	0	0	0	0	0	0	0	1
	SAV	0	0	**2**	0	0	0	0	0	0	2
	DWV	0	0	0	**2**	0	0	0	0	0	2
	DMV	0	0	0	0	**15**	0	0	0	0	15
	DGV	0	0	0	0	0	**8**	0	0	0	8
	SGV	2	0	0	0	0	0	**8**	0	1	11
	MBS	0	0	0	0	0	0	0	**1**	0	1
	SSV	0	0	0	0	1	0	0	0	**11**	12
	Total	5	1	2	2	16	8	9	1	14	**58**
	Percent correct[1]	60	100	100	100	94	100	89	100	79	88

[1] Percent correct determined as number of sites correctly assigned by spectral classification divided by total number of sites assigned by field observation. For total percent correct (last column), the number of correctly assigned sites is the sum of the diagonal entries.

conditions typical of Oasis Valley can be expressed mathematically in terms of principal component energy fluxes as:

$$R_n = H + G + \lambda E \qquad (1)$$

where

R_n is net radiation (energy per area per time);

H is sensible heat flux (energy per area per time);

G is subsurface heat flux (energy per area per time); and

λE is latent heat flux (energy per area per time), where

λ is latent heat of vaporization for water (energy per mass), and

E is rate of water evaporation (mass per area per time).

Net radiation (R_n) is the principal source of the energy available at the surface of the earth and is the algebraic sum of the incoming and outgoing long- and short-wave radiation. Subsurface heat flux (G) is the rate of change at which heat is stored in the soil or water profile directly beneath the earth's surface. Net radiation and subsurface heat flux can be measured or computed in the field using readily available instrumentation. The difference between R_n and G is the energy available at the earth's surface.

Sensible heat flux (H) is the energy that goes into heating the air and is proportional to the product of the temperature gradient and the turbulent transfer coefficient for heat. Latent heat flux (λE) is the energy consumed for evapotranspiration and is proportional to the product of the vapor pressure gradient and the turbulent transfer coefficient for vapor. Neither H nor λE can be determined directly unless the turbulent transfer coefficients are known. Because turbulent transfer coefficients are difficult to determine, indirect methods have been developed to solve the energy budget. One indirect method developed by Bowen (1926) uses the ratio between sensible and latent heat flux ($H/\lambda E$). This ratio and the method that uses this ratio to solve the energy budget are referred to as the Bowen ratio. A detailed derivation of the method and its supporting equations and parameters are given in Laczniak and others (1999). Using this method, ET can be calculated directly from measurable micrometeorological data. This method along with the required micrometeorological data provided the primary means by which ET rates were estimated for the different vegetation and soil environments found in the Oasis Valley discharge area.

Site Selection and Instrumentation

Five sites were selected and instrumented to measure ET. Each site represented an area dominated by a different vegetation type and soil condition. In addition to local vegetation and soil conditions, other factors influencing the selection and location of a site were year-round accessibility, landowner cooperation, and adequate fetch. Generally, fetch (defined as the distance between the sensor and the upwind edge of the environment of interest) implies a homogeneous mix of vegetation types, soils, surface water, or some combination thereof. Sites were located such that the fetch was at least 100 times the height of the highest temperature-humidity sensor (Campbell, 1977). The location and general description of the five sites selected for instrumentation are given in table 3 and plate 1. An additional site at Fairbanks Meadows, originally established as part of a study conducted in Ash Meadows by Laczniak and others (1999), also was maintained as part of this study (table 3).

Each site was equipped with the instrumentation required to measure or compute the micrometeorological data needed to calculate the energy-budget fluxes. Figure 9 presents a schematic showing the typical instrumentation used to determine ET, while figure 10 presents photographs of four actual installations. A typical installation consisted of a net radiometer to measure net radiation, two solid-state air temperature/humidity probes to measure air temperature and relative humidity, two anemometers to measure windspeed, two infrared temperature transducers to measure soil and plant canopy temperatures, and a set of thermocouples and heat flux plates to compute soil heat flux. Instrument pairs were used to measure vertical difference of a particular variable between two reference heights.

Micrometeorological Data and Daily and Annual Evapotranspiration

Micrometeorological data required to solve the energy budget by the Bowen ratio method were collected at each ET site for a period of 1 year or more. A minimum period of 1 year was required to evaluate and document seasonal fluctuations in ET rates and compute an annual ET value. Additional years of data were acquired at most sites to better assess annual changes in ET that may result from climatic variations,

Table 3. Location and general description of and estimated annual evapotranspiration (ET) at five sites in Oasis Valley and one site in Ash Meadows discharge areas that were equipped with micrometeorological instruments, Nevada, 1996–2000

[Abbreviations: lb/ft^3, pounds per cubic foot; in., inches; ft/yr, feet per year]

Site name	Site identifier (pl. 1)	Latitude	Longitude	Altitude [1] (feet above sea level)	Period of data acquisition [Julian days] [2]	Description of dominant vegetation cover [3] and soil moisture conditions [4]	ET-unit identifier [5]	Dry soil density (lb/ft^3)	Percent soil moisture [6]	Estimation period (Julian day) [total days] [2]	Estimation period ET (in.)	Annual ET rate (ft/yr)
Springdale	SDALE	37°01′13″	116°43′49″	3,714.2	May 1996–December 1998 [152–1,072]	Dense cover of meadow and marsh grass; soil wet throughout year	DMV	56	0.80	152–882 [730]	6.27	3.14
Middle Oasis Valley	MOVAL	37°00′39″	116°43′24″	3,690.7	April 1997–January 2000 [481–1,492]	Sparse to moderate cover of wire and saltgrass; soil varies from wet in winter to damp in summer	SGV	88	.15	740–1,470 [730]	4.98	2.49
Upper Oasis Valley Upper	UOVUP	37°03′49″	116°41′39″	3,930	January 1998–September 2000 [745–1,723]	Sparse cover of desert shrubs, primarily wolfberry and rabbitbrush; soil dry	SSV	104	.05	993–1,723 [730]	1.23	.62
Upper Oasis Valley Lower	UOVLO	37°02′42″	116°42′29″	3,861	July 1998–August 2000 [914–1,702]	Moderate to dense cover of desert shrubs, primarily greasewood; soil varies from damp in winter to dry in summer	SSV	59	.12	972–1,702 [730]	2.75	1.38
Upper Oasis Valley Middle	UOVMD	37°02′49″	116°42′41″	3,856	December 1998–September 2000 [1,074–1,723]	Sparse to moderate cover of saltgrass; soil varies from moist in winter to dry in summer	SGV	74	.14	1,358–1,723 [365]	1.63	1.63
Fairbanks Meadows [7]	FMEADW	36°28′59″	116°20′18″	2,249	March 1997–August 2000 [8] [438–1,676]	Dense cover of saltgrass; surface periodically floods during late winter, otherwise soil varies from wet in winter to dry in summer	DGV	71	.30	580–731 [151] 1,097–1,676 [579]	6.14	3.07

[1] Altitudes reported to the nearest foot were estimated from USGS 1:24,000 topographic maps and field observation. Altitudes reported to the nearest tenth of a foot obtained from leveling surveys.

[2] Julian day is day since January 1, 1996.

[3] Vegetation cover descriptors: very sparse, less than 5 percent; sparse, 5 to 25 percent; moderate, 25 to 75 percent; and dense, greater than 75 percent.

[4] Soil moisture descriptors are presented as relative terms.

[5] Descriptions of ET units are given in table 1.

[6] Mean of multiple measurements collected during periods of significant ET.

[7] Site located in Ash Meadows (Laczniak and others, 1999) but maintained as part of Oasis Valley study.

[8] Site destroyed by fire in August 2000.

such as differences between dry and wet years. The period of data acquisition for each instrumented site is given in table 3.

The micrometeorological data collected throughout the study were stored as 20-minute averages computed from measurements made during 10- or 30-second sampling intervals. This collection procedure produced large amounts of data most of which are not presented in this report but are available on request from the USGS's Las Vegas Subdistrict Office. Some gaps occur in the record as a result of instrument failures or the instability of the Bowen ratio (Laczniak and others, 1999). ET values were calculated for each 20-minute period from measured and computed energy fluxes and summed to compute daily ET. Daily values were computed only for days having 68 or more 20-minute computations. Shown in figure 11 are micrometeorological data acquired to solve the energy budget using the Bowen ratio method for the 5-day period, June 7–11, 1997, at the Springdale site (SDALE). Energy-budget fluxes and daily ET calculated from these micrometeorological data are shown in figure 12.

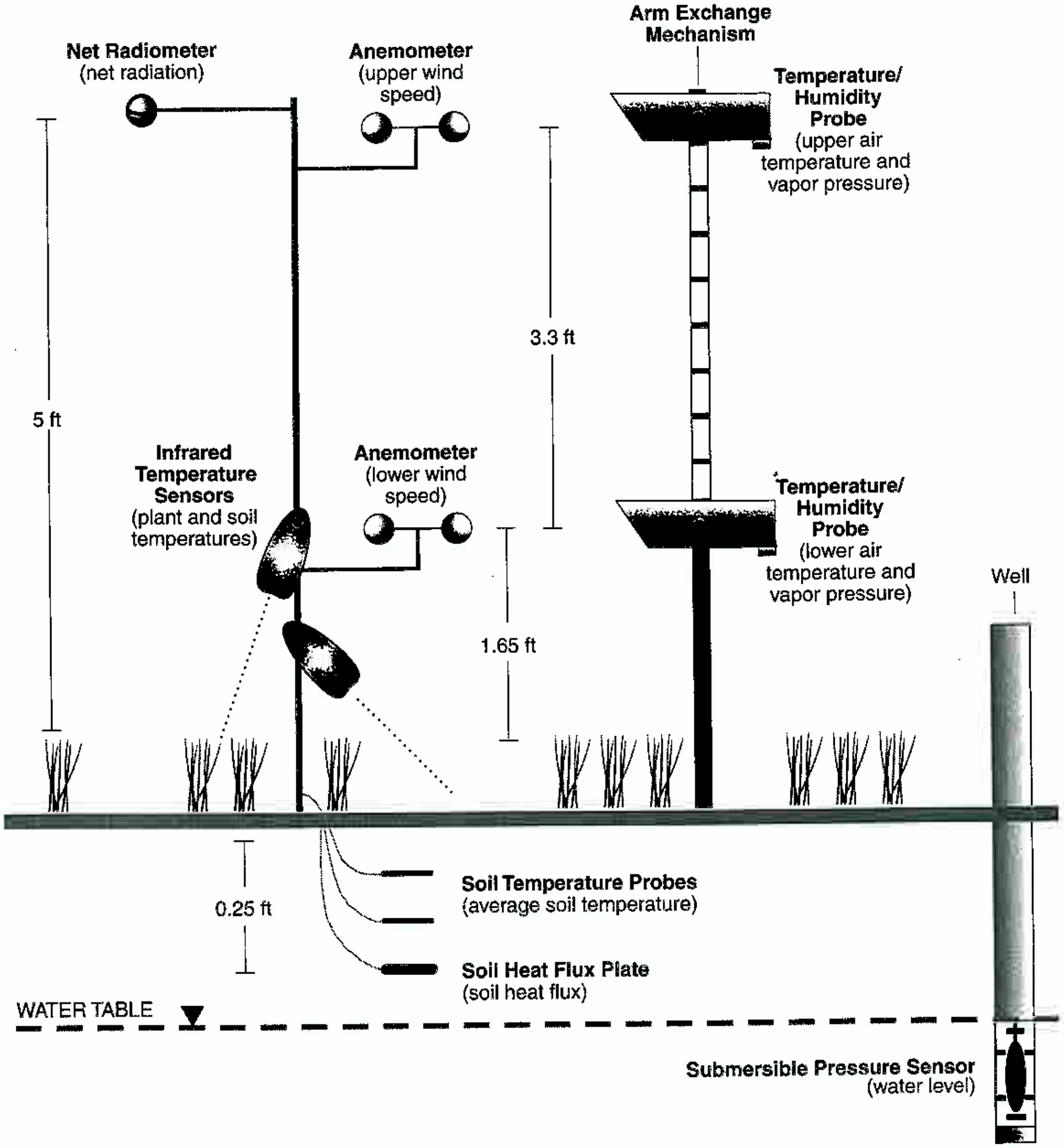


Figure 9. Schematic diagram of instrumentation arrangements installed to measure micrometeorological and water-level data used to determine evapotranspiration from Oasis Valley discharge area, Nevada.

Figure 10. Typical evapotranspiration (ET) stations instrumented to calculate ET rates in Oasis Valley discharge area, Nevada. (*A*) MOVAL site; moderately dense saltgrass with moist soil; (*B*) UOVMD site; sparse saltgrass with dry soil. (*C*) UOVLO site; moderately dense shrubs with dry soil; and (*D*) SDALE site; dense marsh and meadow grasses with wet soil.

Daily ET calculated by the Bowen ratio method at SDALE for 1997 is shown in figure 13. The minimum calculated daily ET was near zero on Julian day 13 (January 13) and the maximum was nearly 0.29 in. on Julian day 187 (July 6). The mean of the daily ET values is 0.106 in. Annual ET for 1997 was 38.7 in. and was computed by adding the daily ET values. Although the plot of daily ET values shows a general pattern defined by higher rates throughout the late spring and summer months, significant daily variability is apparent. Daily variability is due mainly to short-term changes in weather patterns. Smoothing the annual ET curve using an eighth-order polynomial fitted to daily ET values reduced daily variability, while reasonably maintaining the annual value of ET as calculated directly from the daily values. The smoothed ET curve allows for clear graphical comparisons of ET rates computed at different sites and in different years.

Smoothed ET curves developed from data collected at each of the instrumented ET sites are shown on plate 1. An estimate of the average annual ET at each site was computed by integrating daily ET measured over a 1- or 2-year period and is given in table 3. Estimated average annual ET rates differed among ET units and ranged from 3.14 ft over dense meadow vegetation (SDALE) to 0.62 ft over sparse shrubland vegetation (UOVUP). A graph combining all smoothed ET curves for the period of data collection is shown in figure 14*A*. Annual precipitation measurements from 1996 to 2000 are compared to the long-term average in figure 14*B* (National Weather Service, station name: Beatty 8N, station number: 260718-4). Annual precipitation for the 5-year period ranged from 4.7 in. in 1999 to 12.6 in. in 1998 with a long-term average of about 6.3 in. (Desert Research Institute, Western Regional Climate Center, electronic data accessed at <http://www.wrcc.dri.edu/summary/climsmnv.html> on June 17, 2001).

The graph of aggregate ET curves (fig. 14*A*) shows the spatial and temporal differences in ET computed for five sites in Oasis Valley and one site in Ash Meadows. Individual curves show differences in computed daily and annual ET rates between ET units and between sites located within the same ET unit. The intra-unit differences in ET rates at sites located within SGV and SSV were expected considering that the sites were located to evaluate differences in ET rate in areas of different vegetation density. As would be expected, more densely vegetated areas had the larger ET rate. Although temporally limited, ET rates exhibited daily and annual variations. The largest annual variation occurred in 1998. The high ET rates during 1998 are consistent with the much higher-than-normal precipitation measured that year (fig. 14*B*) and likely is a response to increased water availability during that year. The ET curve for MOVAL peaks slightly earlier than curves at other sites. The early peak is explained by the site's location along the Amargosa River. This site is inundated by streamflow in the late winter and early spring, whereas other sites have no similar source of water during this period.

Estimates of Annual Evapotranspiration

An estimate of the mean annual ET from Oasis Valley was computed by summing estimates of the mean annual ET from each of the ET units. ET-unit estimates of the mean annual ET were computed as the product of a unit's acreage and its average ET rate. The average ET rate of an ET unit was determined by averaging all ET rates calculated for sites located within the unit. Site-specific ET rates were calculated from micrometeorological data collected at 5 ET sites in Oasis Valley (table 4) and 9 ET sites in nearby Ash Meadows (Laczniak and others, 1999, table 7). Average ET rates computed from sites in Ash Meadows are considered appropriate for calculating ET rates for ET units in Oasis Valley because vegetation, soil, and meteorological conditions are similar at both locations. A unit having only one ET site within its boundary was assigned an ET rate equal to that of the rate calculated for the lone site. With one exception, the average ET rate of units having two or more sites located within their boundary was computed as the arithmetic mean. The exception was for SSV (sparse shrubland vegetation), where the ET rate was computed as an area-weighted average to reflect the dominance within the unit of the vegetation found at the UOVLO site.Average ET rates for individual ET units range from 1.2 ft/yr for SSV to 8.6 ft/yr for OWB and SAV (table 4). Estimates of mean annual ET range from 8.6 acre-ft at OWB to 2,700 acre-ft at DMV (table 5). The estimate of the mean annual ET from Oasis Valley is 7,800 acre-ft (table 5).

Estimates of mean annual ET include precipitation falling on the area that evaporates or recharges the shallow ground-water flow system and later is evaporated or transpired from within the area. Because the precipitation component of ET is not derived from ground water, it must be removed prior to estimating

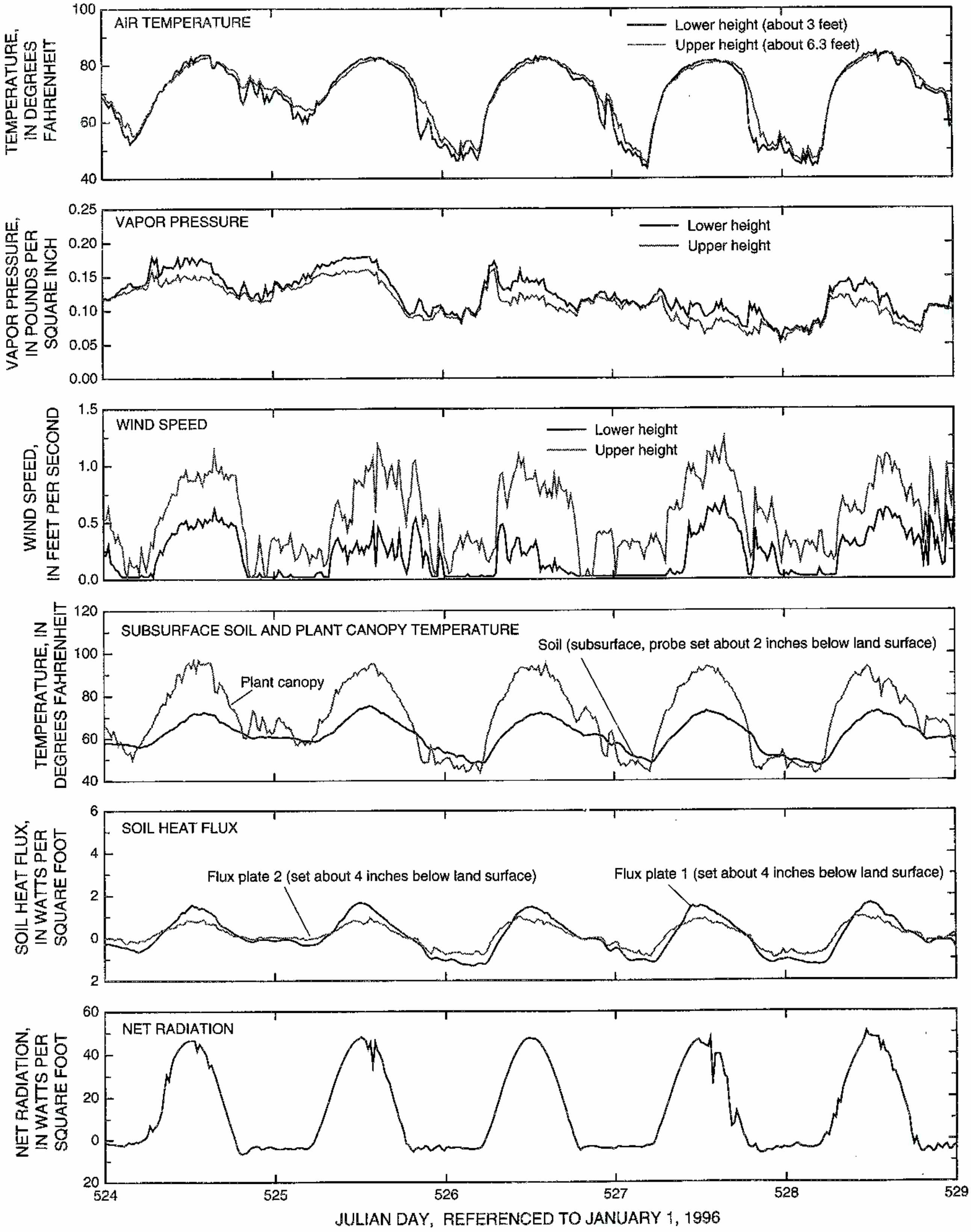


Figure 11. Micrometeorological data collected at Springdale (SDALE) ET site, June 7–11, 1997. Curves constructed from measurements representing 20-minute averaged values.

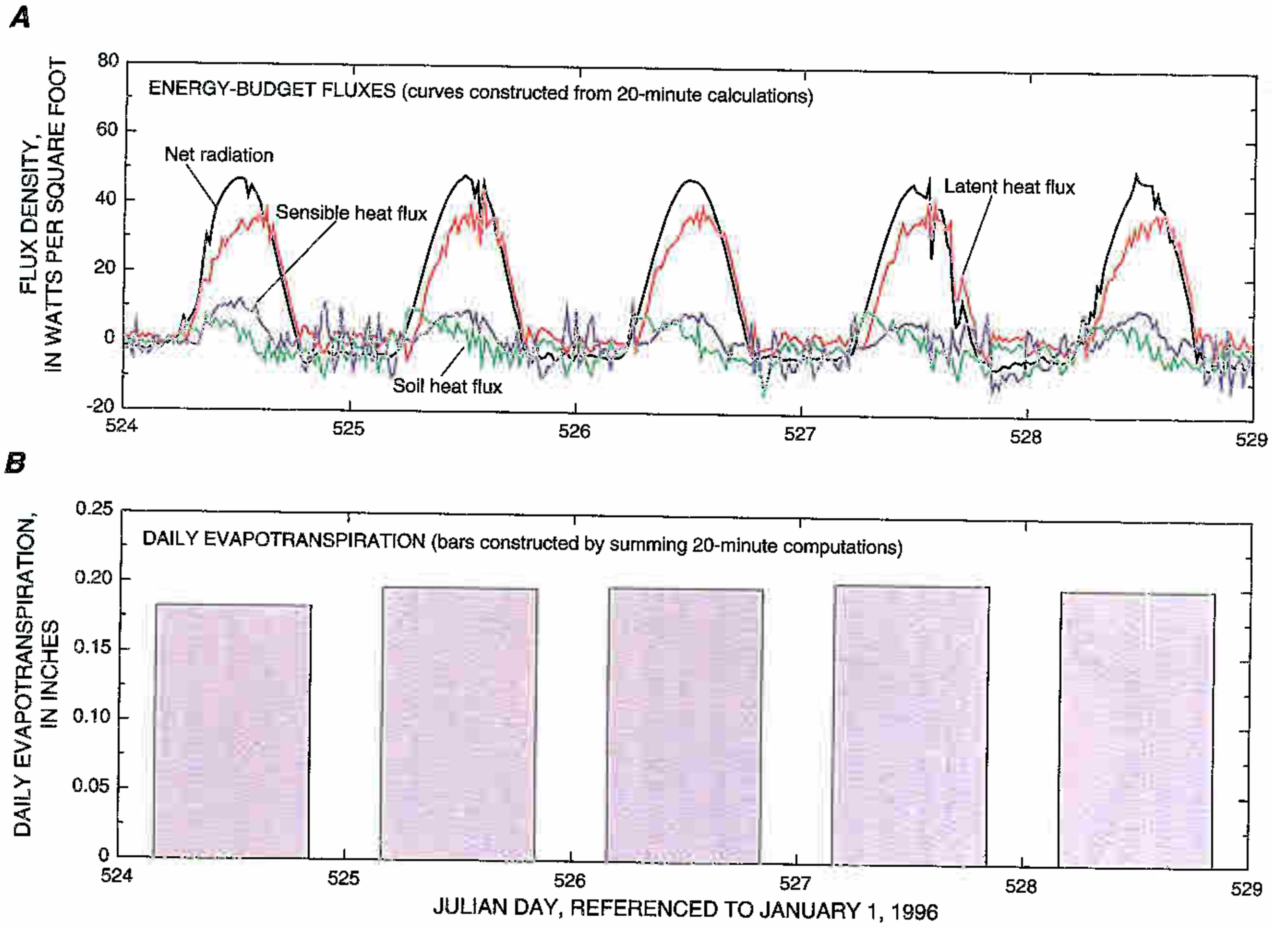


Figure 12. (*A*) Energy-budget fluxes, and (*B*) daily evapotranspiration calculated from micrometeorological data collected at Springdale (SDALE) ET site, June 7–11, 1997.

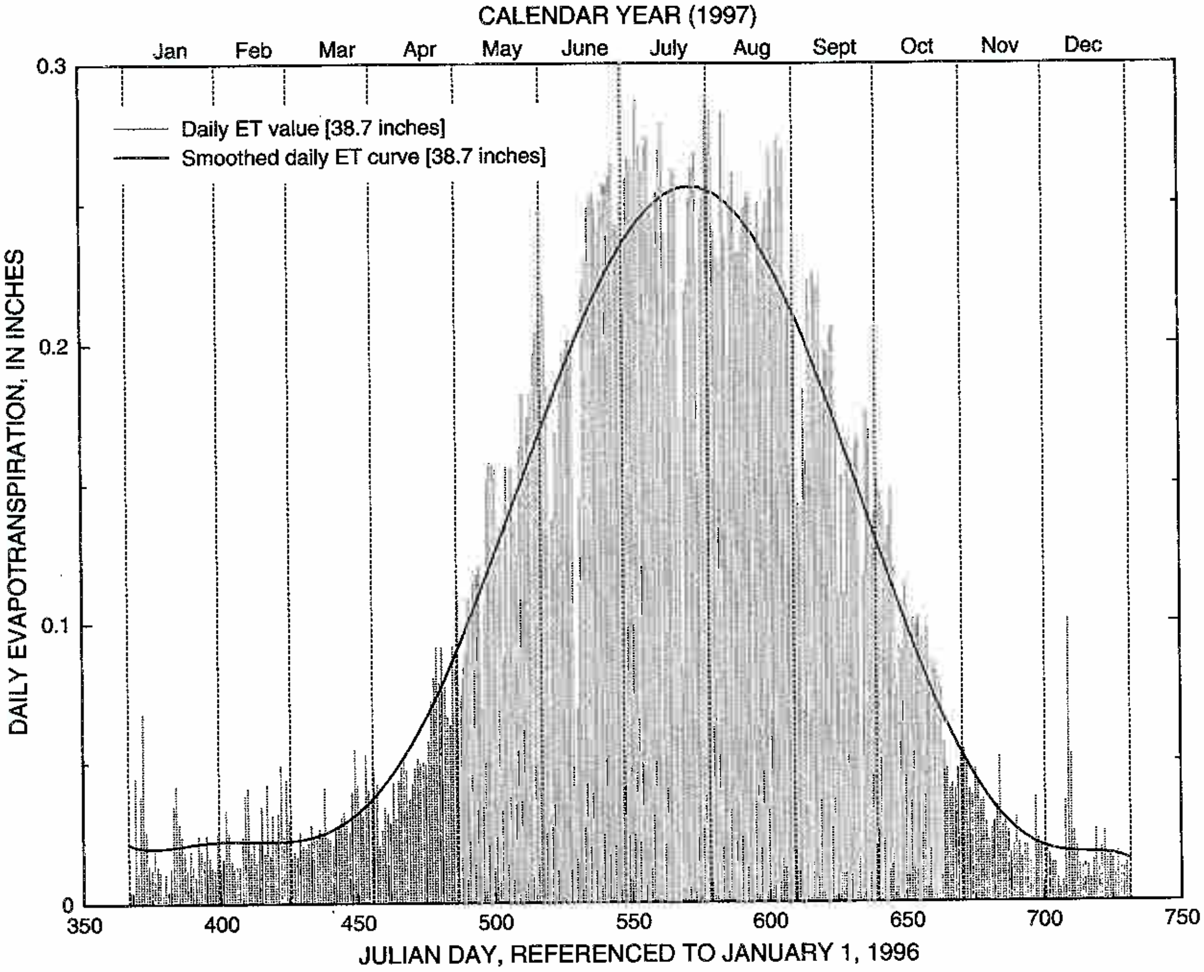


Figure 13. Calculated evapotranspiration (ET) at Springdale (SDALE) ET site, 1997. Number in brackets is annual ET computed for 1997.

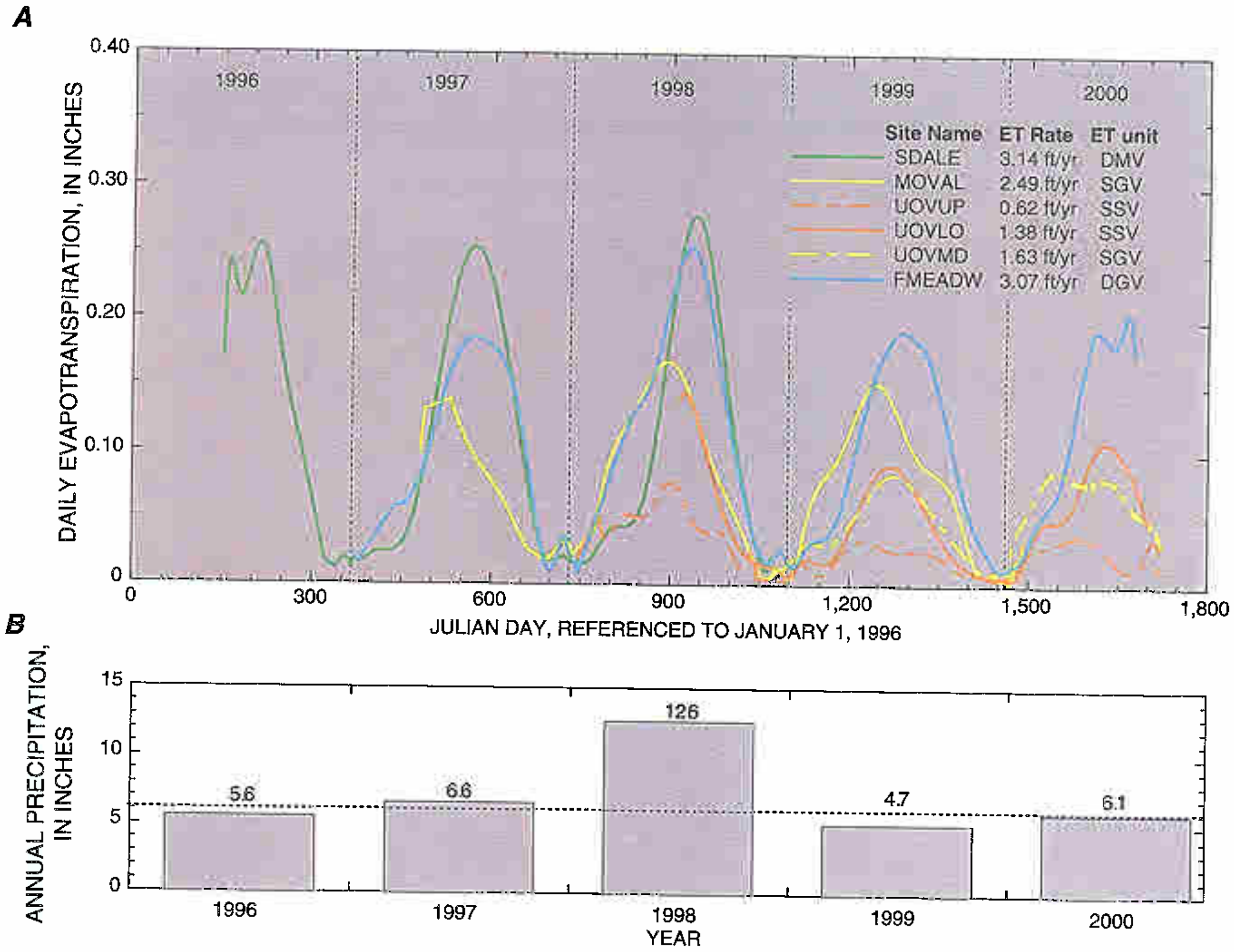


Figure 14. (*A*) Calculated daily evapotranspiration (ET) at five sites in Oasis Valley discharge area and one site (FMEADW) in Ash Meadows discharge area, and (*B*) measured annual precipitation in Oasis Valley, Nevada, 1996–2000. Number above bar is annual total. Dashed line is mean annual precipitation from 1972 to 1999.

Table 4. Evapotranspiration rates used to compute annual evapotranspiration from Oasis Valley discharge area, Nevada

[Abbreviations: AM, Ash Meadows; OV, Oasis Valley; ft/yr, feet per year]

Site name	Location	Site identifier	ET-unit identifier [1]	Measured ET rate (ft/yr) [2]	Average ET rate (ft/yr) [3]
Peterson Reservoir	AM	PRESVR	OWB/SAV	8.60	8.6
Fairbanks Swamp	AM	FSWAMP	DWV	3.91	3.9
Carson Meadow	AM	CMEADW	DMV	3.44	3.3
Springdale	OV	SDALE	DMV	3.14	
Fairbanks Meadow	AM	FMEADW	DGV	3.07	3.2
Rogers Spring 2	AM	RGSPR2	DGV	3.23	
Middle Oasis Valley	OV	MOVAL	SGV	2.49	2.0
Bole Spring South	AM	BSSOUT	SGV	1.88	
Rogers Spring 1	AM	RGSPR1	SGV	1.92	
Upper Oasis Valley Middle	OV	UOVMD	SGV	1.63	
Lower Crystal Flat	AM	LCFLAT	MBS	2.58	2.6
Bole Spring North	AM	BSNORT	MBS	2.60	
Upper Oasis Valley Lower	OV	UOVLO	SSV	1.38	1.2
Upper Oasis Valley Upper	OV	UOVUP	SSV	.62	

[1] ET unit descriptions are given in table 1 of this report and in table 7 of Laczniak and others (1999).

[2] Rates for sites in Ash Meadows taken from Laczniak and others (1999, table 7) and in Oasis Valley from table 3 in this report.

[3] Average rate is computed as arithmetic mean of measured rates for each ET unit except for SSV. Average rate for SSV is area-weighted average.

ground-water discharge. The precipitation component was removed by decreasing the ET rate by an amount equivalent to the average annual precipitation. The remaining ET is assumed to be that derived from ground water. Removing all the average annual precipitation reasonably assumes that no precipitation leaves the Oasis Valley discharge area as runoff during average conditions.

Mean annual precipitation was estimated from bulk precipitation measurements collected during the study and long-term measurements taken at National Weather Service station Beatty 8N. The average annual precipitation determined from long-term measurements (1972–99) was 6.3 in. (electronic data accessed at <http://www.wrcc.dri.edu/summary/climsmnv.html> on June 17, 2001). Based on this average and bulk precipitation measurements, a reasonable estimate of mean annual precipitation for the Oasis Valley area is 6 in. (fig. 14). Mean annual ground-water ET rates were estimated by subtracting the mean annual precipitation (0.5 ft) from the mean annual ET rate (table 5). As applied, this adjustment assumes that the only source of water other than ground water is the rain falling directly on an ET unit's surface. This assumption discounts as potential sources any water originating from the infiltration of local surface runoff or precipitation falling on the surface of areas of no substantial ground-water ET. Although a limitation, these assumptions are considered reasonable because local surface runoff is minimized by (1) the fractured nature of the volcanic ridges within the area, and (2) low and infrequent rainfall. In addition, limited available data indicate that much of the local surface runoff occurring throughout the region evaporates before entering the discharge area.

Mean annual ground-water ET from Oasis Valley was estimated by summing the mean annual ground-water ET from each ET unit. Mean annual ground-water ET from each ET unit was computed as the product of the unit's acreage and mean average ground-water ET rate. Estimates of mean annual ground-water ET from individual ET units range from 8.1 acre-ft at OWB and SAV to 2,300 acre-ft at DMV (table 5). The estimate of the mean annual ground-water ET from Oasis Valley is 6,000 acre-ft (table 5).

The estimate of mean annual ground-water ET differs by a factor of 3 from that of Malmberg and Eakin (1962, p. 25). Their estimate of 2,000 acre-ft assumes that there are 3,800 acres of phreatophytes in Oasis Valley and an average ET rate of 0.5 ft/yr, whereas the 6,000 acre-ft estimated in this study assumes that there are 3,426 acres of phreatophytes and moist bare soil and an average ET rate of 1.7 ft/yr (table 5). There is a difference of about 10 percent in the estimated

Table 5. Estimated mean annual evapotranspiration and ground-water evapotranspiration by evapotranspiration unit from Oasis Valley discharge area, Nevada

[Mean annual values are reported to two significant digits. Abbreviation: acre-ft, acre-foot; ft/yr, feet per year]

ET-unit identifier[1]	ET-unit acreage (acres)	Average ET rate (ft/yr)[2]	Mean annual ET (acre-ft)[3]	Average ground-water ET rate (ft/yr)[4]	Mean annual ground-water ET (acre-ft)[5]
OWB	1	8.6	8.6	8.1	8.1
SAV	4	8.6	34	8.1	32
DWV	40	3.9	160	3.4	140
DMV	832	3.3	2,700	2.8	2,300
DGV	340	3.2	1,100	2.7	920
SGV	1,215	2.0	2,400	1.5	1,800
MBS	102	2.6	270	2.1	210
SSV	892	1.2	1,100	.7	620
Total	3,426	[6]2.3	7,800	[6]**1.7**	6,000

[1] ET unit described in table 1.

[2] Average rate is that given in table 4.

[3] Annual ET computed as product of ET unit acreage and average ET rate.

[4] ET rate adjusted to remove water contributed by precipitation. Adjustment applied assumes an average annual precipitation of 0.5 feet.

[5] Annual ground-water ET computed as product of ET unit acreage and average ground-water ET rate.

[6] Rate is area weighted-average.

acreages. The primary discrepancy between the two estimates, however, is the result of the difference in the estimated average ET rate. Although the accuracy of one rate estimate versus the other is difficult to evaluate, the more localized nature of the data and more rigorous method used in this study are likely to result in a more accurate estimate of the ET rate.

Limitations of Methodology

The accuracy of the estimate of ground-water discharge via ET is limited by the assumptions inherent in the classification procedure and the energy-budget method (Bowen ratio) used to compute daily ET. The classification procedure identified 3,426 acres of Oasis Valley as an area from which ground water is being lost by evapotranspiration. The remaining portion of Oasis Valley is assumed to be an area of no substantial ground-water loss. This assumption, although strongly supported by this area's lack of vegetation, dryness of soil, and greater depths to the water table, could result in some error in the estimate of ground-water discharge by ET. Although the remaining portion of the valley is large (about 30,000 acres), the rate of ground-water discharge by ET is likely less than 0.01 ft/yr (Andraski, 1997, p. 1913), thus the volumetric loss would be minimal.

ET-unit acreage was delineated on the basis of TM imagery acquired in 1992. Precipitation data reported for nearby weather stations indicate that rainfall for 1992 was slightly above normal, a level that may have produced healthier vegetation and moister soils. Classifying ET units on the basis of multiple years of imagery would likely result in acreage estimates more representative of the long-term average.

Other limitations include (1) the assumption that all springflow is ultimately evaporated or transpired from within the bounds of one of the delineated ET units; (2) the short-term nature of the data used to compute mean values; (3) the limited number of sites used to estimate ET from each ET unit, (4) the uncertainty in the adjustment applied to remove precipitation from ET estimates, and (5) local ground-water recharge from areas outside ET unit boundaries. The mean annual ET estimates of each ET unit (table 5) were computed from Oasis Valley and Ash Meadows data typically acquired over a period of 2 or more years. Although the period of data collection included years of varying climatological conditions, variations are fairly small in the annual ET rates computed from one year to the next and between sites within the same ET unit. ET estimates determined from longer-term data and additional ET-site installations would help refine, improve, and provide more confidence in any estimate of mean annual ground-water discharge.

The adjustment applied to remove precipitation from estimated ground-water discharge discounts as potential recharge sources (1) water originating from infiltration of local surface runoff, or (2) precipitation falling on the surface of areas of no substantial ground-water ET. This infiltration probably is minimal and most likely evaporates before entering the shallow ground-water system. Any amount of infiltration that does flow into areas of ground-water discharge may be balanced by any ground water that flows out of areas of substantial ground-water discharge into unclassified areas. The lack of available data about infiltration limits our ability to adjust ET rates for it and may result in larger estimated ground-water discharge values. However, these estimated values may still be compared with previous ground-water discharge estimates in Oasis Valley that also were not adjusted for these infiltration processes (Malmberg and Eakin, 1962).

Subsurface Outflow

At the southern and western boundaries of the Oasis Valley discharge area, the alluvial and welded-tuff aquifers thin and pinch out against less-permeable Paleozoic and Precambrian siliciclastic rocks (fig. 2). The boundary between these aquifers and less-permeable rocks forces ground water to flow either toward land surface, where it is evapotranspired, or out of Oasis Valley, where it is termed "subsurface outflow." The most likely pathway for subsurface outflow is through the alluvial aquifer via the alluvium-filled channel of the Amargosa River at the Amargosa Narrows (figs. 3 and 15). This subsurface outflow would move southward into the Amargosa Desert. Other potential but less likely pathways for subsurface outflow are to the southeast across a ridge separating Oasis Valley from Crater Flat (Fridrich and others, 1999) and to the south beneath the Bullfrog Hills. Flow through the basement confining unit beneath the alluvial aquifer is considered negligible considering its very low permeability (Fridrich and others, 1999). The range of hydraulic conductivity values of this basement confining unit probably is three to seven magnitudes of order less than that of the alluvial aquifer (Winograd and Thordarson, 1975; Bedinger and others, 1989).

Assuming that all subsurface flow occurs through the alluvium within the Amargosa River channel and knowing the hydraulic gradient, cross-sectional geometry, and hydraulic conductivity of the channel fill material, an estimate of subsurface outflow can be calculated using Darcy's law.

Darcy's law as modified by Heath (1989, p. 12) can be expressed as:

$$Q = 0.0084\, K\, A\, (dh/dl), \qquad (2)$$

where

Q is quantity of ground water flow, in acre-feet per year;

K is hydraulic conductivity, in feet per day;

A is cross-sectional area through which flow occurs, perpendicular to the direction of flow, in square feet;

(dh/dl) is the hydraulic gradient, in feet per foot; and

0.0084 is the factor to convert cubic feet per day into acre-feet per year.

The hydraulic gradient through the Amargosa Narrows area was calculated from depth-to-water measurements and spring altitudes in the vicinity of Amargosa Narrows (see "Spring Discharge" section, plate 2). Based upon the calculated gradient, ground-water flow generally is to the south. The gradient changes as ground water travels from Beatty south-southeast to the Amargosa Narrows. Gradients are about 0.010 ft/ft at section B-B′, 0.017 ft/ft near the mouth of the Amargosa Narrows, and 0.0044 ft/ft south of the Amargosa Narrows. Although some seasonal fluctuations in the water table occur, the effect on the hydraulic gradient is negligible.

Geophysical information, including data from seismic refraction and downhole geophysical logging (D.L. Berger and A.R. Robledo, U.S. Geological Survey, written commun., 1999), geologic mapping, and lithologic logs, was used to estimate the thickness and cross-sectional area of the alluvium-filled channel at the Amargosa Narrows area. One in-line and three transverse cross-sections at the Amargosa Narrows illustrate the variability in the thickness and cross-sectional area of the alluvium (fig. 15). The cross-sectional area of saturated alluvium is approximately 230,000 ft^2 at cross-section B-B′ north of the Amargosa Narrows, 88,000 ft^2 at cross-section C-C′ at the northern entrance of the Amargosa Narrows, and 248,000 ft^2 at cross-section D-D′ south of the Amargosa Narrows. The alluvial aquifer at the Amargosa Narrows is somewhat funnel-shaped in that its width decreases and thickness

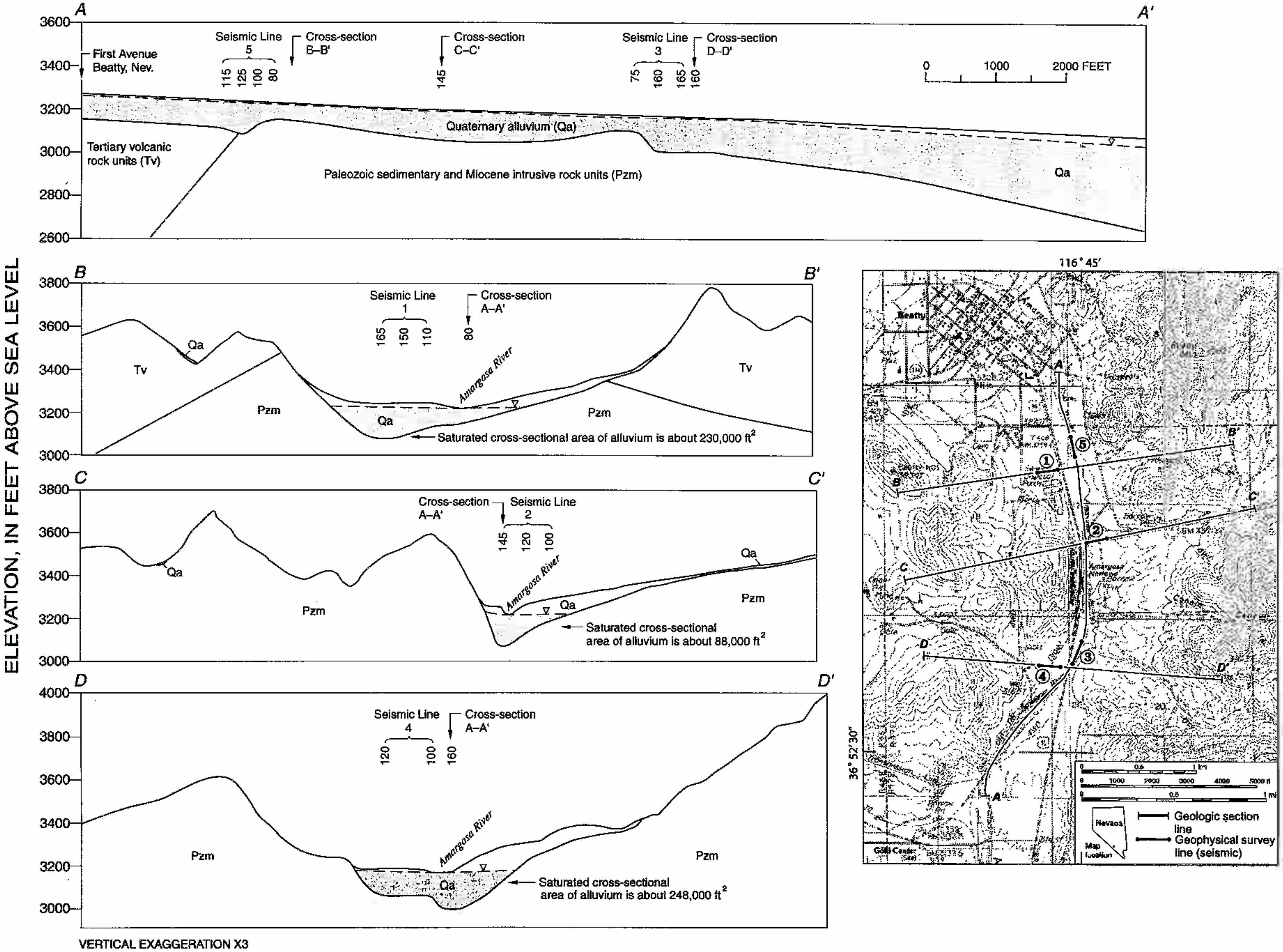


Figure 15. Geologic cross-sections showing distribution of valley-fill sediments, Amargosa Narrows area, Nevada. Vertically oriented numbers are depths to bedrock estimated from geophysical surveys or from companion cross-section.

increases approaching the Amargosa Narrows area. At Amargosa Narrows, the aquifer's width is at its narrowest; upon exiting both its width and thickness increase.

Results of aquifer tests conducted in the Death Valley regional ground-water flow system in basin-fill deposits similar to those found at the Amargosa Narrows were used to estimate the hydraulic conductivity of the alluvium (W.A. Belcher, U.S. Geological Survey, oral commun., 2001). Based on these tests, a range defined by two standard deviations from the geometric mean of hydraulic conductivity is 2 to 10 ft/day. The range may be biased toward higher values because most wells tested were constructed for ground-water production and may not best represent common basin-fill deposits.

Substituting a hydraulic gradient of 0.017 ft/ft, a cross-sectional area of 88,000 ft^2, and the range of 2 to 10 ft/day for hydraulic conductivity into Darcy's law results in a computed outflow that ranges between 30 and 130 acre-ft/yr. This subsurface outflow estimate is limited by the accuracy of the calculated or estimated hydraulic gradient, cross-sectional area, and hydraulic conductivity. The estimate is less than the previous estimate of 400 acre-ft/yr (Malmberg and Eakin, 1962), but still supports the concept of limited subsurface outflow when compared to total ground-water discharge in Oasis Valley. The difference between these estimates probably is related in part to the more rigorous quantification of parameters affecting subsurface outflow applied in this study. Additional test boreholes in the alluvium, seismic-refraction surveys, and geophysical borehole logging are needed to better quantify the parameters needed to estimate subsurface outflow from Oasis Valley.

Ground-Water Withdrawal

Ground water is withdrawn from wells scattered throughout Oasis Valley. The largest single user of ground water is the Beatty Water and Sanitation District (BWSD), which supplies water to most homes and businesses within the town of Beatty. Outside of Beatty, springs and non-municipal wells supply most of the homes and ranches in Oasis Valley with water for irrigation, livestock, and domestic uses.

The BWSD pumps ground water from seven wells. Location, construction, and open-interval data for these wells are given in table 6. Six of these wells are in Oasis Valley—Beatty Middle, Summit, and Upper Indian wells are in the Bullfrog Hills, and Beatty wells 1, 2, and 3 are in the town of Beatty. A seventh well, EW-4[1], is southwest of Beatty in the Amargosa Desert. Table 7 gives monthly and annual ground-water withdrawals by well for 1996 to 1999 (J.C. Weeks, BWSD, written commun., 2000).

Total annual ground-water withdrawal from the six BWSD wells in Oasis Valley declined from 410 acre-ft in 1996 to 179 acre-ft in 1999 (fig. 16). Water pumped from outside Oasis Valley at well EW-4 compensated for much of this decrease, but overall withdrawal still declined. Production from this well started in the fall of 1997 and increased from 115 acre-ft in 1998 to 155 acre-ft in 1999 (table 7).

Ground-water withdrawal by the BWSD varies in response to seasonal water demands (fig. 17). The largest demands occur in summer (July through September) and the smallest in winter (January through March). The seasonal variation in ground-water withdrawal from Oasis Valley has lessened (fig. 17) since 1997. Although demands continued to vary seasonally in 1998 and 1999, the larger summer needs were met primarily by water pumped from well EW-4 outside of Oasis Valley.

Water-level measurements indicate that the reduction in municipal ground-water withdrawal from Oasis Valley may have affected local water levels. Water levels measured in the Lower Indian Springs Well in Bullfrog Hills have risen since February 1999 (pl. 2). This rise is consistent with decreased ground-water withdrawal from the Beatty Upper Indian and Beatty Middle wells (table 7).

Field reconnaissance and Nevada Division of Water Resources drilling records identified approximately 15 springs and 20 non-municipal wells that supply water to individual homes and ranches in Oasis Valley. A reasonable estimate of annual ground-water withdrawal consumed from each of these sources is 1 acre-ft (Coache, 1999). Based on this consumption rate and the number of supply sources, a reasonable estimate of the annual non-municipal use of ground water from Oasis Valley is 35 acre-ft. Estimates of the total annual ground-water withdrawal from Oasis Valley, computed by combining municipal and non-municipal estimates, are 440 acre-ft in 1996 and

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[1] Well EW-4 is not shown in the figures or on the plates that accompany this report.

Table 6. Characteristics of water-supply wells used by the Beatty Water and Sanitation District, Oasis Valley and Amargosa Desert, Nevada, 1996–99

[Data source for construction information is Nevada Division of Water Resources drilling logs]

Well name: Wells are grouped by Nevada hydrographic area and within each area are listed in alphabetical order.

USGS site identification (ID): The standard site identification is based on the grid system of latitude and longitude. The number consists of 15 digits. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote the degrees, minutes, and seconds of longitude; and the last two digits (assigned sequentially) identify the sites within a 1-second grid. For example, site 365619116483901 is at 36°56′19″N latitude and 116°48′39″W longitude, and is the first site recorded in that 1-second grid. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are determined.

Local site number: A local site identification is used in Nevada to identify a site by hydrographic area (Rush, 1968) and by the official rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each site designation consists of four units: The first unit is the hydrographic area number. The second unit is the township, preceded by an N or S to indicate location north or south of the base line. The third unit is the range, preceded by an E to indicate location east of the meridian. The fourth unit consists of the section number and letters designating the quarter section, quarter-quarter section, and so on (A, B, C, and D indicate the northeast, northwest, southwest, and southeast quarters, respectively), followed by a number indicating the sequence in which the site was recorded. For example, site 228 S11 E46 34ACAD 1 is in the Oasis Valley (Hydrographic Area 228). It is the first site recorded in the southeast quarter of the northeast quarter of the southwest quarter of the northeast quarter of section 34, township 11 south, range 46 east, Mount Diablo base line and meridian.

Land-surface altitude: Datum is sea level. Altitudes reported to nearest foot were estimated from U.S. Geological Survey 1:24,000 topographic maps and field observation.

Well depth: Datum is land surface.

Top of open Interval: Depth below land surface of uppermost well opening.

Bottom of open interval: Depth below land surface of lowermost well opening.

Type of open interval: P, perforated or slotted casing; R, wire-wound screen; S, screen.

Well name	USGS site ID	Latitude	Longitude	Local site number	Land-surface altitude (feet)	Well depth (feet)	Depth to open interval		Type of open interval	Contributing lithologic unit
							Top (feet)	Bottom (feet)		
Oasis Valley										
Beatty Middle Well	365619116483901	36°56′19″	116°48′39″	228 S11 E46 34ACAD 1	4,110	700	160	680	R	Volcanic rock
Beatty Summit Well	365527116475301	36°55′27″	116°47′53″	228 S12 E46 02BDAC 1	3,882	700	240	700	S	Volcanic rock
Beatty Upper Indian Well	365709116481101	36°57′09″	116°48′11″	228 S11 E46 26BCDC 1	4,240	693	200	690	S	Volcanic rock
Beatty Well No. 1	365524116444001	36°55′24″	116°44′40″	228 S12 E47 06DCC 1	3,365	200	95	160	P	Valley fill
Beatty Well No. 2	365409116452301	36°54′09″	116°45′23″	228 S12 E47 07DBC 1	3,290	195	90	195	S	Valley fill
Beatty Well No. 3	365420116453001	36°54′20″	116°45′30″	228 S12 E47 07DBD 1	3,300	300	70	300	P	Valley fill
Amargosa Desert										
[1]EW-4	365000116492301	36°50′00″	116°49′23″	230 S13 E46 03BC 1	3,230	1,417	677	1,400	P, S [2]	Valley fill

[1] Well EW-4 is not shown in the figures or on the plates that accompany this report.

[2] Alternating open intervals of perforated/slotted casing and screen.

Table 7. Monthly ground-water withdrawals measured by Beatty Water and Sanitation District, Oasis Valley and Amargosa Desert, Nevada, 1996–99

[Well locations are given in table 6. Symbol: —, data missing or non-applicable]

Well Name: Wells are grouped by Nevada hydrographic area and within each area are listed in alphabetical order.

Withdrawal measurement: Measurements provided by Beatty Water and Sanitation District. Withdrawal values are reported in acre-feet to three significant digits.

		Ground-water withdrawal (acre-feet)												
Name of well	Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual total [1]
							Oasis Valley							
Beatty Middle Well	1996	0	0	0	0	—	—	—	1.35	1.75	1.4	1.66	1.34	7.5
	1997	1.32	1.90	2.25	1.89	1.11	1.22	1.70	1.16	1.37	1.58	0.119	1.79	17.4
	1998	1.99	1.69	1.81	1.29	1.41	.491	.86	1.07	.583	.522	.368	.46	12.5
	1999	.307	0	0	0	0	0	0	0	0	0	0	0	.307
Beatty Summit Well	1996	5.53	5.86	4.92	5.55	5.44	5.35	5.35	5.84	5.26	4.98	5.47	4.95	64.5
	1997	5.72	4.85	4.61	4.9	5.04	4.7	4.93	4.91	4.87	4.81	3.00	4.41	56.7
	1998	4.88	4.2	4.6	5.25	6.57	5.95	5.03	6.57	4.23	3.96	3.04	4.08	58.4
	1999	4.82	4.36	3.34	3.9	3.84	3.34	5.06	5.86	6.51	8.01	6.29	4.45	59.8
Beatty Upper Indian Well	1996	10.9	11.5	9.41	10.8	10.7	10.4	10.30	10.6	10.4	9.61	10.90	9.86	125
	1997	11.6	9.77	9.44	10.1	10.4	9.82	9.02	11	10.2	10.1	5.50	7.42	114
	1998	8.28	7.43	8.07	9.27	11	10.3	8.71	10.8	6.9	6.51	4.73	6.08	98.1
	1999	6.54	6.17	4.69	5.55	4.91	4.91	7.3	8.9	10.1	12.3	10.80	6.57	88.6
Beatty Well No. 1	1996	4.24	4.51	3.79	4.19	4.27	3.85	3.59	3.91	3.88	2.58	3.24	2.07	44.1
	1997	4.48	3.82	4.19	4.18	3.99	3.51	3.4	3.24	2.93	2.98	2.96	3.09	42.8
	1998	3.31	3.47	3.44	4.02	4.17	4.66	3.59	3.65	3.28	2.42	3.59	3.65	43.3
	1999	3.87	3.87	3.62	4.02	3.87	3.87	3.13	2.24	.123	.221	.144	.00921	29
Beatty Well No. 2	1996	3.09	0	0	0	0.486	10.3	11.3	11.2	11.5	9.99	3.18	1.04	62.1
	1997	.579	.000307	2.21	8.86	1.8	0	7.57	11.1	3.85	13.3	6.24	0	55.5
	1998	0	0	0	0	0	0	0	0	0	0	0	0	0
	1999	0	0	0	0	0	0	0	0	0	0	0	0	0
Beatty Well No. 3	1996	.0988	3.45	3.54	12	20.5	14.1	17	20.2	9.54	3.97	2.27	0.64	107
	1997	.918	.203	0	0	11.8	15.6	19.3	12.3	19.6	2.16	4.15	0	86
	1998	0	0	0	0	.552	0	1.53	3.34	3.47	6.11	2.91	.123	18
	1999	0	0	0	0	0	0	0	0	1.63	0	0	0	1.63
							Amargosa Desert							
[2]EW-4	1997	—	—	—	—	—	—	—	—	—	—	1.9	4.86	6.76
	1998	1.17	3.44	.43	2.61	5.55	9.11	18.4	20.5	22	16.6	11.7	3.71	115
	1999	5.46	3.5	8.96	12.2	14.3	23.8	22.8	22.5	19.5	12	6.14	3.56	155

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[1] Total annual ground-water withdrawal may not equal the total of reported monthly ground-water withdrawals because of rounding to significant digits.

[2] Beatty Water and Sanitation District began using this well as a water-supply well in November 1997.

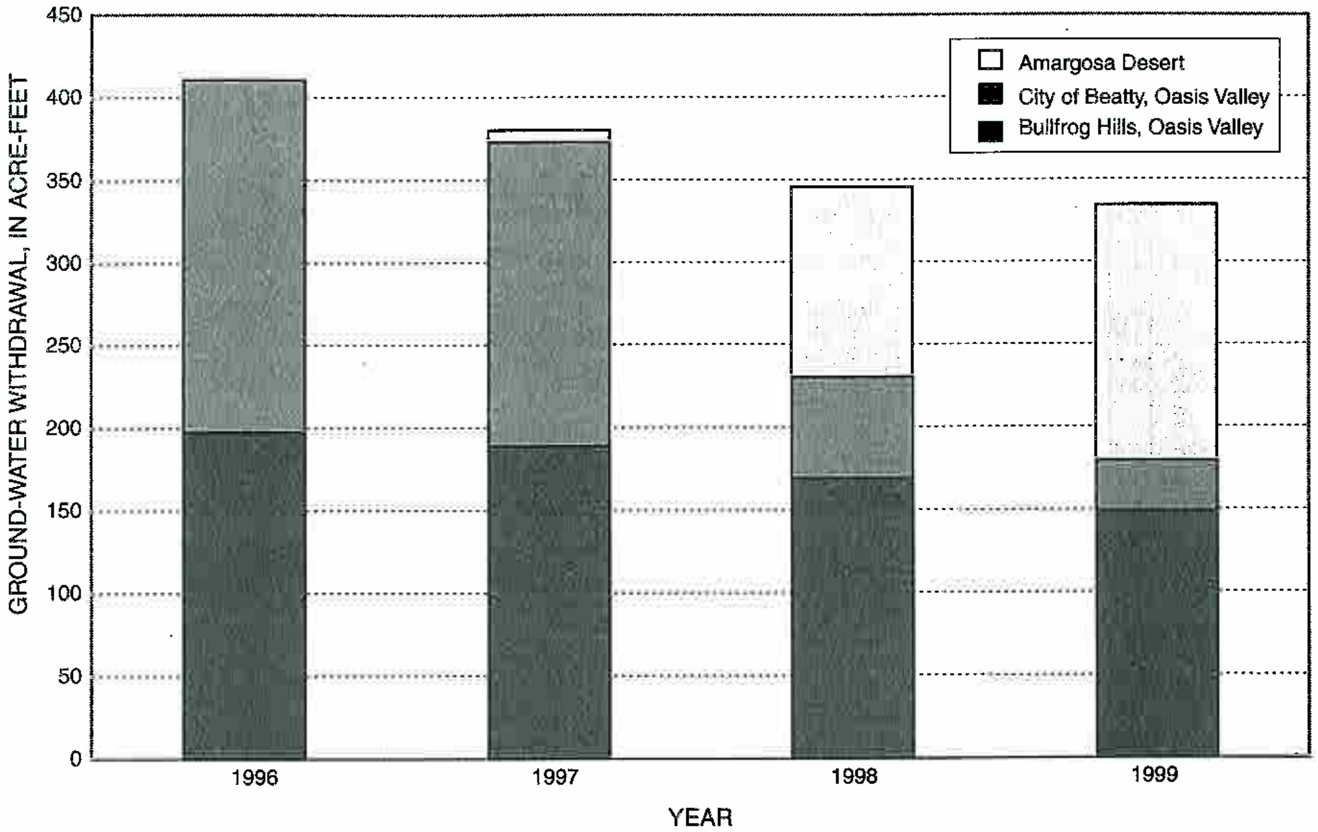

Figure 16. Comparison of annual ground-water withdrawal by the Beatty Water and Sanitation District from Oasis Valley and Amargosa Desert, Nevada, 1996–99.

210 acre-ft in 1999. Monitoring non-municipal water consumption would improve the accuracy of the estimate.

Spring Discharge

Spring discharge was measured periodically at sites throughout Oasis Valley from 1996 to 1999. Measurement sites were distributed geographically throughout the valley (pl. 2; table 8). About half the sites were located where springflow could be measured near or at a single spring orifice. Measuring locations for these sites, referred to as spring sites, were natural outlet channels or man-made outflows such as plastic or metal pipe draining the springhead or pool. Other springs and seeps were more difficult to measure because the discharge is diffuse. Discharge from these springs and seeps was measured at a more downgradient location, referred to as a channel site, where flow converged and channelized. Typically these channel flow measurements included contributions from a combination of nearby springs, seeps, and local shallow ground-water inflow. Evapotranspiration and other ground-water recharge may occur upstream from these sites.

Periodic spring-discharge measurements were made monthly from November 1996 to September 1997, quarterly from October 1997 to September 1998, and semi-annually from October 1998 to September 1999. On occasion, a site could not be measured because of difficulties in accessing the site. More frequent measurements were made at selected channel sites to better evaluate seasonal and annual changes in discharge. Table 9 gives the maximum and minimum measured discharge and the magnitude of discharge fluctuation at each site for each year of data collection. Measurements may not be indicative of the actual minimum or maximum discharge due to their periodic nature. Local precipitation affects channel site measurements but has little or no effect on spring site measurements (table 9).