U.S. Department of the Interior
U.S. Geological Survey

Estimates of Ground-Water Discharge as Determined From Measurements of Evapotranspiration, Ash Meadows Area, Nye County, Nevada

Water-Resources Investigations Report 99-4079

Prepared in cooperation with the
OFFICE OF ENVIRONMENTAL RESTORATION AND WASTE MANAGEMENT
U.S. Department of Energy
Nevada Operations Office, under
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By Randell J. Laczniak, Guy A. DeMeo, Steven R. Reiner, J. LaRue Smith, and Walter E. Nylund

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Carson City, Nevada
1999

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Box 25286
Denver, CO 80225-0286

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
Length		
foot (ft)	0.3048	meter
inch (in.)	25.4	Millimeter
mile (mi)	1.609	Kilometer
Area		
acre	0.4047	square hectometer
Volume		
acre-foot (acre-ft)	0.001233	cubic hectometer
Energy Flux		
watts per square feet (W/ft^2)	0.0929	watt per square meter
Pressure		
pound per square inch (lb/in^2)	6.89476	KiloPascal
Velocity or Rate		
foot per year (ft/yr)	0.3048	meters per year
foot per second (ft/s)	0.3048	meters per second
Volumetric Rate		
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
gallons per minute (gal/min)	0.0631	liter per second

Temperature: Degrees Fahrenheit can be converted to degrees Celsius by the formula °C = (°F – 32) x 0.556.

Sea level: Sea level refers to the National Geodetic Vertical Datum of 1929 (NVGD of 1929), which formerly has been called the "Sea-Level Datum of 1929." The Datum is derived from a general adjustment of the first-order leveling networks across 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.

Symbol or Acronym and Definitions

C_a	Specific heat of air at a constant pressure
C_s	Specific heat of dry soil
C_w	Specific heat of water
d_{bls}	Depth below land surface at which heat flux is measured
d_{bws}	Depth below water surface over which temperature is measured
de/dz_e	Vapor pressure gradient near the Earth's surface
DGV	Dense grassland vegetation
DMV	Dense meadow vegetation
dT/dz_t	Temperature gradient near the Earth's surface
DWV	Dense wetland vegetation
E	Rate of water evaporation
e	Vapor pressure
E_a	Available energy
$e_{l,u}$	Vapor pressure at lower or upper reference point
ERP	Environmental Restoration Program
ET	Evapotranspiration
G	Subsurface heat flux
H	Sensible heat flux
HF_s	Heat flux through soil at some measurement depth
k_h	Turbulent transfer coefficient of heat in air
k_v	Turbulent transfer coefficient of vapor
MBS	Moist bare soil
NTS	Nevada Test Site
OWB	Open-water body
P	Ambient air (barometric) pressure
R_{Li}	Incoming long wave radiation
R_{Lo}	Outgoing long wave radiation
R_n	Net radiation
R_{Si}	Incoming short wave radiation
R_{So}	Outgoing short wave radiation
SAV	Submerged aquatic vegetation
SGV	Sparse grassland vegetation
SPOT	*Systeme Probatoire d'Observation de la Terre*
T	Temperature
$T_{l,u}$	Temperature at lower or upper reference point
TM	Thematic mapper
USDOE	United States Department of Energy
USGS	United States Geological Survey
W	Gravimetric soil water content
z_e	Height at which vapor pressure is measured
z_t	Height at which temperature is measured
dT_s	Change in soil temperature between surface and soil heat flux measurement depth per unit time
dT_w	Change in water temperature per unit time
ε	Ratio of molecular weight of water to dry air
γ_c	Psychrometric constant
λ	Latent heat of vaporization for water
λE	Latent heat flux
ρ_a	Density of air
ρ_{Bs}	Bulk density of soil
ρ_w	Density of water

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

ABSTRACT

Ash Meadows is one of the major discharge areas within the regional Death Valley ground-water flow system of southern Nevada and adjacent California. Ground water discharging at Ash Meadows is replenished from inflow derived from an extensive recharge area that includes the eastern part of the Nevada Test Site (NTS). Currently, contaminants introduced into the subsurface by past nuclear testing at NTS are the subject of study by the U.S. Department of Energy's Environmental Restoration Program. The transport of any contaminant in contact with ground water is controlled in part by the rate and direction of ground-water flow, which itself depends on the location and quantity of ground water discharging from the flow system. To best evaluate any potential risk associated with these test-generated contaminants, studies were undertaken to accurately quantify discharge from areas downgradient from the NTS. This report presents results of a study to refine the estimate of ground-water discharge at Ash Meadows.

The study estimates ground-water discharge from the Ash Meadows area through a rigorous quantification of evapotranspiration (ET). To accomplish this objective, the study identifies areas of ongoing ground-water ET, delineates unique areas of ET defined on the basis of similarities in vegetation and soil-moisture conditions, and computes ET rates for each of the delineated areas. A classification technique using spectral-reflectance characteristics determined from satellite images recorded in 1992 identified seven unique units representing areas of ground-water ET. The total area classified encompasses about 10,350 acres dominated primarily by lush desert vegetation. Each unique area, referred to as an ET unit, generally consists of one or more assemblages of local phreatophytes. The ET units identified range from sparse grasslands to open water. Annual ET rates are computed by energy-budget methods from micrometeorological measurements made at 10 sites within six of the seven identified ET units. Micrometeorological data were collected for a minimum of 1 year at each site during 1994 through 1997. Evapotranspiration ranged from 0.6 foot per year in a sparse, dry saltgrass environment to 8.6 feet per year over open water. Ancillary data, including water levels, were collected during this same period to gain additional insight into the evapotranspiration process. Water levels measured in shallow wells showed annual declines of more than 10 feet and daily declines as high as 0.3 foot attributed to water losses associated with evapotranspiration.

Mean annual ET from the Ash Meadows area is estimated at 21,000 acre-feet. An estimate of ground-water discharge, based on this ET estimate, is presented as a range to account for uncertainties in the contribution of local precipitation. The estimates given for mean annual ground-water discharge range from 18,000 to 21,000 acre-feet. The low estimate assumes a large contribution from local precipitation in computed ET rates; whereas, the high estimate assumes no contribution from local precipitation. The range presented is only slightly higher than previous estimates of ground-water discharge from the Ash Meadows area based primarily on springflow measurements.

INTRODUCTION

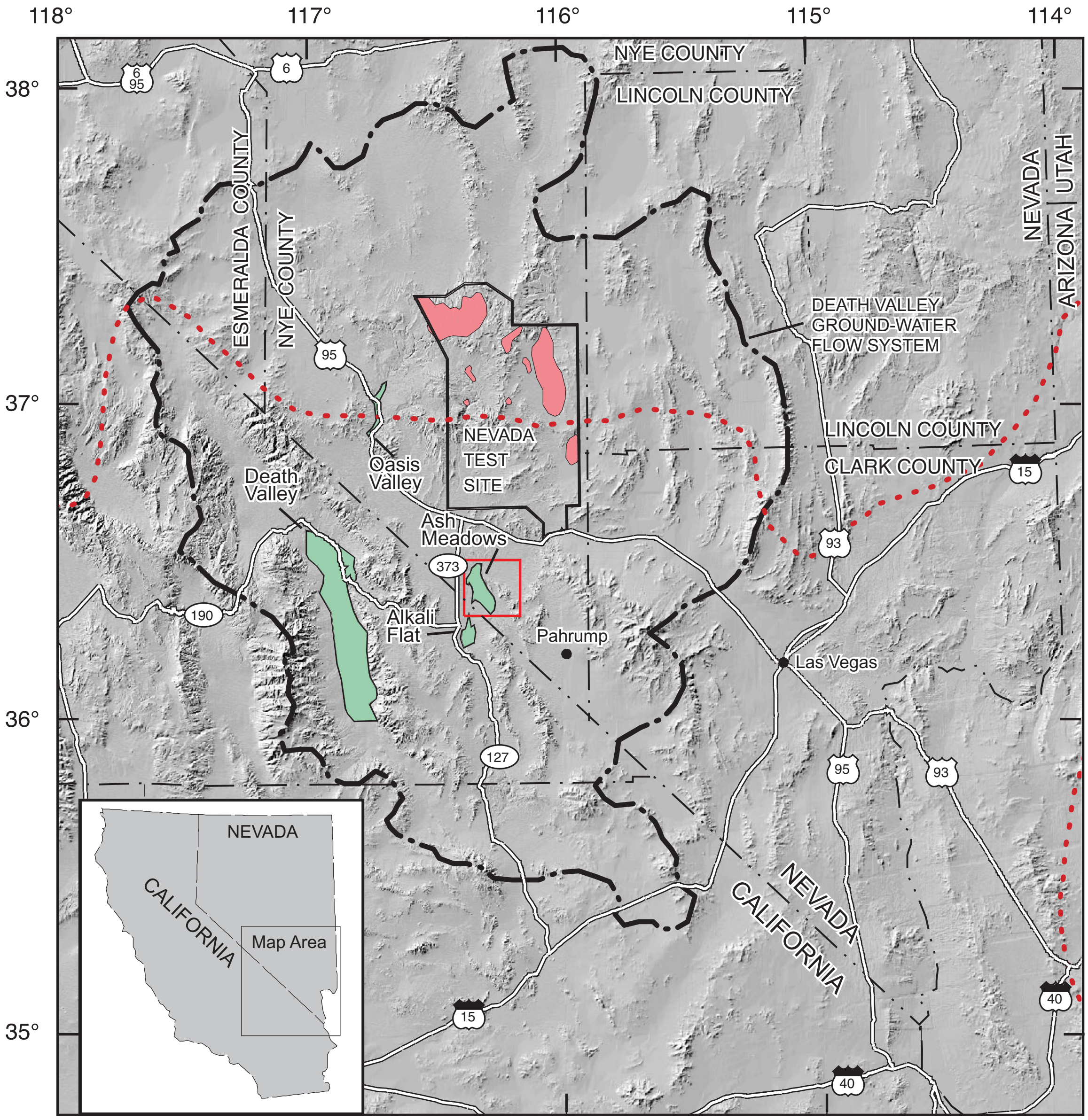
Ash Meadows is one of only a few areas of natural discharge within a large, regionally extensive ground-water basin known as the Death Valley ground-water flow system (fig. 1). This flow system, as defined by Harrill and others (1988), extends hundreds of miles over a geologically complex, arid to semi-arid region of southern Nevada and adjacent parts of California. Centrally located within the boundaries of this flow system is the Nevada Test Site (NTS), which historically has been the primary continental-based location for testing nuclear devices. As a consequence of about 40 years of nuclear testing at this facility, significant quantities of radioactive and other chemical contaminants have been released into the subsurface at depths whereby many contaminants are in contact with ground water. Once within the ground-water system, contaminants are subjected to local flow conditions, and although retarded by chemical and physical processes, can begin moving in consonance with ground water. Ground water beneath the NTS generally moves southward and westward toward one of four areas of major natural ground-water discharge: (1) Ash Meadows, (2) Oasis Valley, (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 under its Environmental Restoration Program (ERP). As part of this program, the U.S. Department of Energy will evaluate the risk that these contaminants pose to the public. To accomplish this objective, the potential for contaminant migration must be determined and the hydrologic factors controlling their transport must 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 downgradient 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 the uncertainty in the current estimates of ground-water discharge, the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, began a series of studies in 1993 designed to refine and improve previous estimates of ground-water discharge throughout the region.

The discharge area chosen for study first, was Ash Meadows. This selection was based in part on (1) the close proximity of the area to past locations of underground testing (less than 50 mi, fig. 1); (2) the potential for rapid water and contaminant transport through the highly fractured carbonate-rock aquifers contributing water to the area (Winograd and Pearson, 1976); (3) the availability of data acquired by previous and ongoing studies; and (4) the significance placed on the area as a National Wildlife Refuge and as the sole habitat for many threatened and endangered plants and animals native to the region. Additional investigations to refine estimates of ground-water discharge at other major discharge areas influencing ground-water flow away from the NTS are planned or are in progress as "follow ups" to the Ash Meadows study.

Purpose and Scope

The purpose of the study is to refine and improve the current estimate of ground-water discharge from the Ash Meadows area. The estimate of ground-water discharge presented in this report is computed from evapotranspiration rates determined from field measurements of micrometeorological data and extrapolated over the study area on the basis of similarities in vegetation, soil-moisture characteristics, and depth to ground water. This report presents the results of the study, describes the general approach used to determine ground-water discharge from evapotranspiration estimates, and documents and describes the methods used to measure evapotranspiration and extrapolate these measurements throughout the Ash Meadows region. The methods employed required the collection of micrometeorological data and water levels on a nearly continual basis. This intense data-collection effort generated a substantial amount of climatic and hydrologic data during the period of study (October 1993 through September 1997) that may be of value to other investigations of the region's climate, ecology, and hydrology. 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 Nichols and Rapp (1996), Nichols and others (1997), and the U.S. Geological Survey (1994-98), or can be requested from the Las Vegas office of the U.S. Geological Survey.



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.

0 20 40 MILES

0 20 40 KILOMETERS

EXPLANATION

Area of underground nuclear testing
—Modified from Laczniak and others (1996)

Area of ground-water discharge
—Modified from Laczniak and others (1996)

Area of plates 1 and 2

Extent of Mojave Desert ecoregion—Taken from Bailey (1995)

Figure 1. Ash Meadows and other major areas of natural discharge within Death Valley ground-water flow system potentially influencing ground-water flow at Nevada Test Site.

Acknowledgments

The authors express their appreciation to all agencies that cooperated in this study. These agencies include the U.S. Department of Energy, U.S. Fish and Wildlife Service, National Park Service, and Bureau of Land Management. The authors also thank the many individuals who contributed to the completion of the study. In particular, the authors extend thanks to David Ledig, and Beth and David St. George, U.S. Fish and Wildlife Service, who not only provided valuable assistance with access to many sensitive areas controlled and maintained as part of the Ash Meadows National Wildlife Refuge, but more importantly, taught us much about the ecology of the area's plants and wildlife. The authors also acknowledge William D. Nichols of the U.S. Geological Survey for his valuable insight into the techniques and instrumentation applied to measure evapotranspiration in arid environments of the southwest. And lastly, the authors wish to thank and express their appreciation to the many private landowners in the area that openly provided access to their property and extended their hospitality to project personnel having the opportunity to visit this unique and interesting part of the world. The genuine interest expressed by all involved in this effort was most greatly appreciated.

Location and Jurisdiction

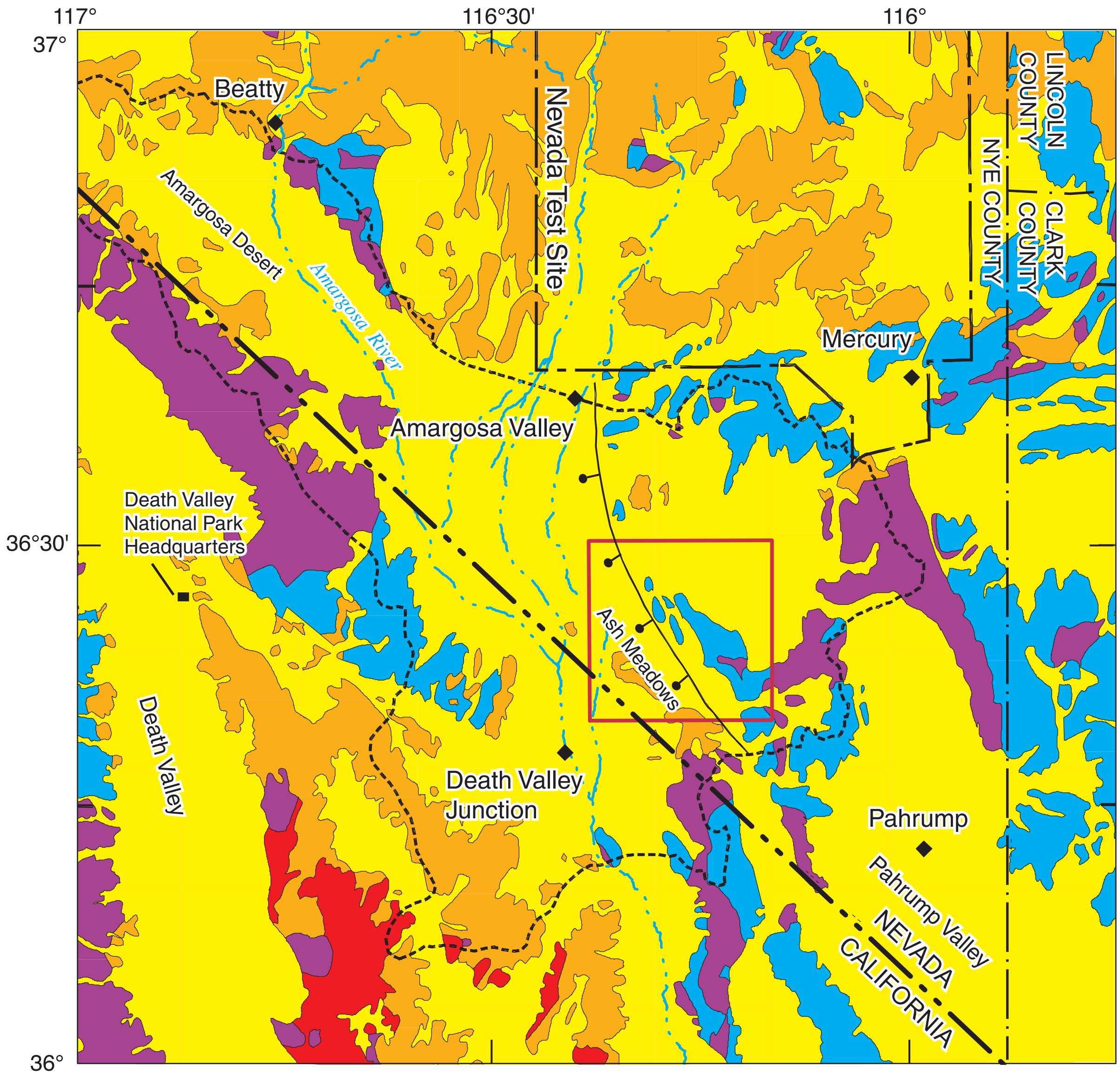
Ash Meadows is in southern Nye County, Nev. (figs. 1 and 2), about 40 mi east of the Death Valley National Park headquarters near Furnace Creek Ranch, Calif., and 90 mi northwest of Las Vegas, Nev. The boundaries of Ash Meadows are not well established, but where defined loosely, the general area covers about 50,000 acres of desert uplands and spring-fed oases (Sada, 1990). Most of Ash Meadows is within southern Nevada, but some acreage, depending on boundary definition, may extend across the state line into California (fig. 3). About 23,000 acres of this total make up the Ash Meadows National Wildlife Refuge (U.S. Fish and Wildlife Service, 1988). The U.S. Fish and Wildlife Service controls most of the land within the refuge, with some acreage held by the Bureau of Land Management. Together these agencies manage the refuge under a plan to restore and maintain the area as a natural ecosystem—the intent being the preservation of the local flora and fauna. Devils Hole (fig. 3) and a surrounding 40-acre tract are part of Death Valley National Park maintained and managed by the National Park Service. A few small-acreage parcels within the refuge remain in private holding.

General Description and Setting

Ash Meadows lies within the southern part of the Great Basin, an internally drained subdivision of the Basin and Range physiographic province. The dominant physiographic features 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 isolate north-trending mountain ranges from similar 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 clastic rocks constitute the primary rock type of the hills, ridges, and mountain ranges in the area. The intermontane basins are filled with sedimentary and volcanic rocks (valley fill), including sandstone, siltstone, lacustrine claystone and limestone, and volcanic ash and lava flows.

Ash Meadows sits at the southern end of the Amargosa Desert within the Amargosa Desert Hydrographic Area[1] (fig. 2). The valley is not a typical Basin-and-Range valley in that it is oriented northwest-southeast as a consequence of right-lateral movement along strike-slip faults bounding the valley to the north and south. Although positioned on the floor of the Amargosa Desert valley and typified by a gently, southwesterly sloping terrain that ranges in altitude from about 2,100 to 2,400 ft above land surface, Ash Meadows' easternmost extent includes a series of low carbonate-rock hills referred to by Carr (1988) as the Amargosa Ridges. These local hills, although thousands of feet lower in altitude than the major mountain ranges that rim the valley, starkly contrast with the surrounding valley floor and protrude upward by as much as 900 ft forming fairly steep carbonate-rock outcrops.

[1] Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Rush, 1968; Cardinalli and others, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities.



Base from U.S. Geological Survey digital data, 1:100,000, 1978-89: Universal Transverse Mercator Projection Zone 11.

0 10 20 MILES

0 10 20 KILOMETERS

Geology generalized from Strietz and Stinson (1974) and Stewart and Carlson (1978)

EXPLANATION

Generalized geologic units

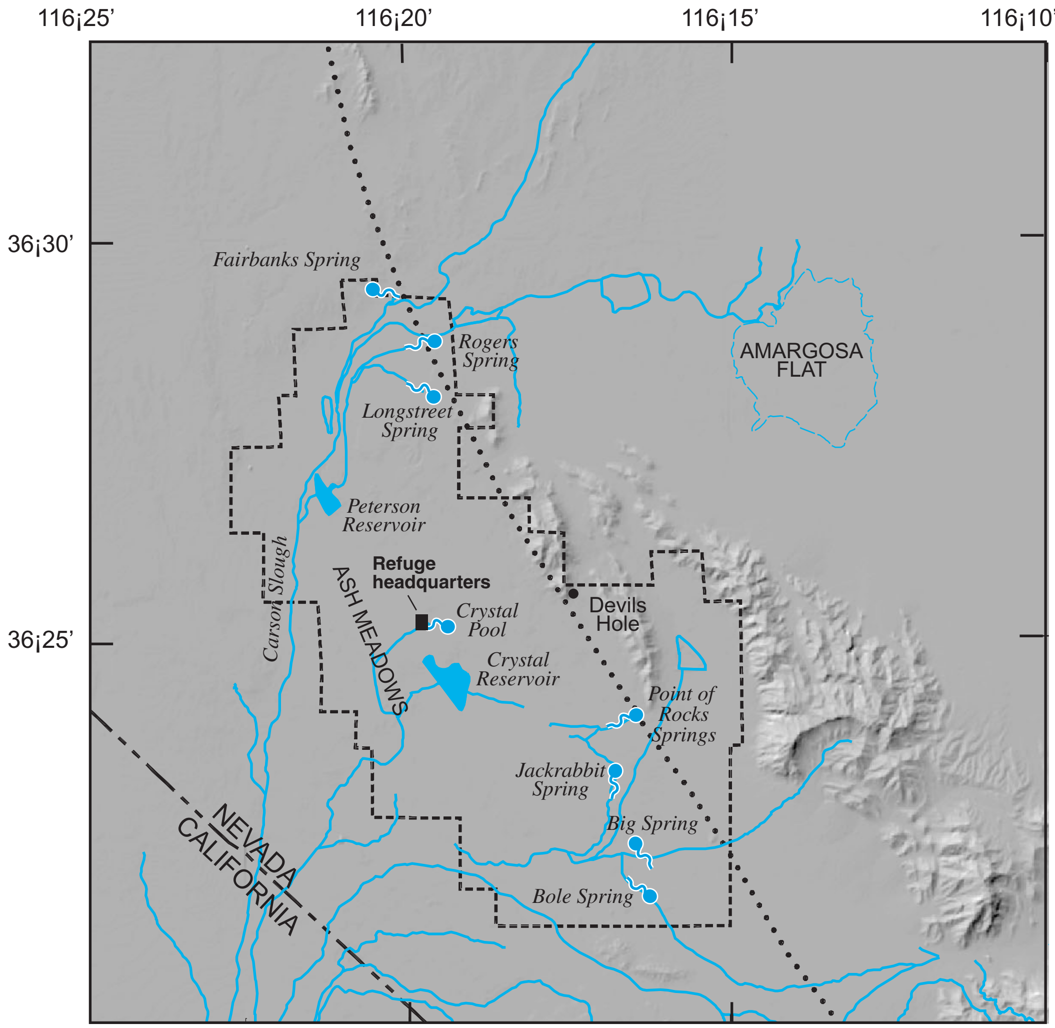
- Cenozoic valley fill
- Cenozoic volcanic rock
- Mesozoic intrusive rock
- Paleozoic carbonate rock
- Paleozoic/Precambrian clastic (siliceous) rock

Boundary of Amargosa Desert hydrographic area—From Harrill and others (1988); Rush (1968); Cardinalli and others (1968)

Approximate trace of Ash Meadows fault system—Shown only in vicinity of Ash Meadows

Area of plates 1 and 2

Figure 2. Generalized geology of Ash Meadows area, Nevada and California.



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;
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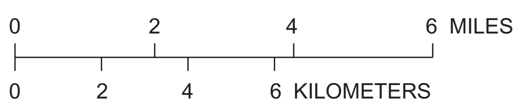


EXPLANATION

- - - - - - - **Boundary of Ash Meadows National Wildlife Refuge**—From U.S. Fish and Wildlife Service (1988)

• • • • • • **Approximate trace of Ash Meadows fault system**

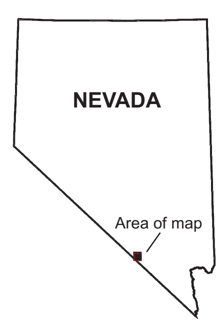


Figure 3. Major hydrographic and physiographic features in Ash Meadows area, Nevada.

Located in the north-central part of the Mojave Desert (fig. 1), the Ash Meadows area is typical of most other desert regions in that it is characterized by short mild winters, long hot summers, and low annual rainfall. Long-term climatic data specific to Ash Meadows are lacking, but estimates of mean annual values can be inferred from information available for nearby National Weather Service stations at Amargosa Farms, Nev. (latitude 36° 34′ N., longitude 116° 28′ W., altitude 2,450 ft); at Beatty, Nev. (latitude 37° 00′ N., longitude 116° 43′ W., altitude 3,550 ft); at Pahrump, Nev. (latitude 36° 12′ N., longitude 115° 59′ W., altitude 2,670 ft); and in Death Valley near Furnace Creek Ranch, Calif. (latitude 36° 28′ N., longitude 116° 52′ W., altitude 194 ft below sea level). Mean annual precipitation at the four National Weather Service stations ranges from about 2 to 6 inches. On the basis of these values, a reasonable estimate of the mean annual precipitation at Ash Meadows is between 2.5 and 4.25 inches. Sada (1990, p. 3) describes average annual rainfall for Ash Meadows at less than 2.75 inches. Mean annual temperature at these same weather stations ranges from about 60 to 77°F. A reasonable estimate of the mean annual temperature for Ash Meadows is about 65°F. Annual precipitation determined from rainfall data collected in Ash Meadows as part of this study was 4.3 inches in 1995, 2.4 inches in 1996, and 4.0 inches in 1997. The annual mean temperature measured at a weather station, maintained as part of this study at the National Wildlife Refuge headquarters (fig. 3), was 65°F in 1995 and 66°F in 1996. The minimum temperature recorded at the weather station during this 2-year period was 19°F and the maximum temperature was 112°F.

Unlike most desert communities, Ash Meadows has a high concentration of springs. More than 30 springs and seeps are aligned in an approximate linear pattern spanning about 10 mi. Springflow varies substantially across the area with a maximum measured discharge of nearly 3,000 gal/min at Crystal Pool (fig. 3). The combined measured discharge has been estimated at about 10,500 gal/min, equivalent to about 17,000 acre-ft/yr of water (Walker and Eakin, 1963; Winograd and Thordarson, 1975; Dudley and Larson, 1976). More than 80 percent of the measured springflow discharges from nine of the springs. Although long-term discharge measurements are not available at every spring and seep, periodic measurements made at many of the major springs indicate that springflow has been fairly constant throughout recent history (Tim Mayer, U.S. Fish and Wildlife Service, written commun., 1997). The only exception was in the late 1960's and early 1970's when local agricultural interests pumped large quantities of ground water to irrigate local fields (Dudley and Larson, 1976). During this period of extensive pumping, local springflows decreased and water levels declined throughout much of the area. One major consequence of ground-water depletion was a drop in the pool level in Devils Hole, a shaft-like opening into the ground-water system through carbonate (limestone and dolomite) bedrock created by a collapse into a steeply dipping fault-controlled fissure. The ground-water pool provides the sole remaining natural habit for the endangered Devils Hole pupfish (*Cyprinodon diabolis*). The potential effects of pool decline on the continued existence of the pupfish compelled the U.S. Supreme Court to establish a minimum pool level for Devils Hole, essentially prohibiting any significant pumpage from the local area. Shortly after the mandate, all agricultural and development interests in the area faded, water levels began recovering, and springflows returned to nearly the previously measured rates (Westenburg, 1993).

A large diversity of plants, fish, and local wildlife are dependent on water provided by the numerous local springs scattered throughout the area. Many plants and animals are native to the area, which is distinguished as having the largest concentration of endemic species of any locale in the continental United States (U.S. Fish and Wildlife Service, 1988). Spring pools and associated drainages provide habitat to several species of fish and a few rare aquatic insects. Vegetation throughout the area is diverse with denser growths concentrated along spring pools and drainages, and poorly drained bottomland. The vegetation provides food and shelter to numerous birds, insects, reptiles, and small mammals. Plant assemblages and species are numerous and include many varieties of grasses, reeds, shrubs, and trees. Areas influenced by local springflow include groves of ash (*Fraxinus velutina* var. *coriacea*), cottonwood (*Populus fremontii*), willow (*Salix exigua*), and mesquite (*Prosopis glandulosa torreyana* and *P. pubescens*); thick stands of saltcedar (*Tamarix aphylla, T. parviflora,* and *T. ramosissima*); expansive meadows of saltgrass (*Distichlis spicata* var. *stricata*), wire-grass (*Juncus balticus, J. cooperi,* and *J. nodosus*), and bunch grass (*Sporobolus airoides*); and open marshland of cattails (*Typha domingensis*), reeds (*Phragmites australis*), and bulrush (*Scirpus robustus*). More typical Mojave Desert flora, primarily sparse covers of healthy creosote bush (*Larrea tridentata*), saltbush (*Atriplex canescens* and *A. polycarpa*) and desert holly (*A. hymemelytra*), dominate upland areas not influenced by local spring discharge.

The primary drainage within Ash Meadows is Carson Slough (fig. 3), a local tributary of the Amargosa River (fig. 2). Carson Slough is intermittent and seldom flows through its entire extent, except after infrequent storms. Short reaches of the slough, directly downgradient from major springs, flow throughout the entire year. The length of reach flowing and the amount of flow varies during the year with longer, more continuous, and greater flows in winter, when temperatures are cooler and vegetation is dormant, thus reducing local water losses through evapotranspiration. Numerous small, unnamed channels, which exhibit seasonal fluctuations in flow similar to Carson Slough, drain many of the larger local springs. A few irrigation ditches and impoundments (Crystal and Peterson Reservoirs, fig. 3) constructed to support past human activities in the area remain. Most other manmade structures have been removed as part of the management plan being implemented by the U.S. Fish and Wildlife Service (USFWS) to return the area to a natural ecosystem.

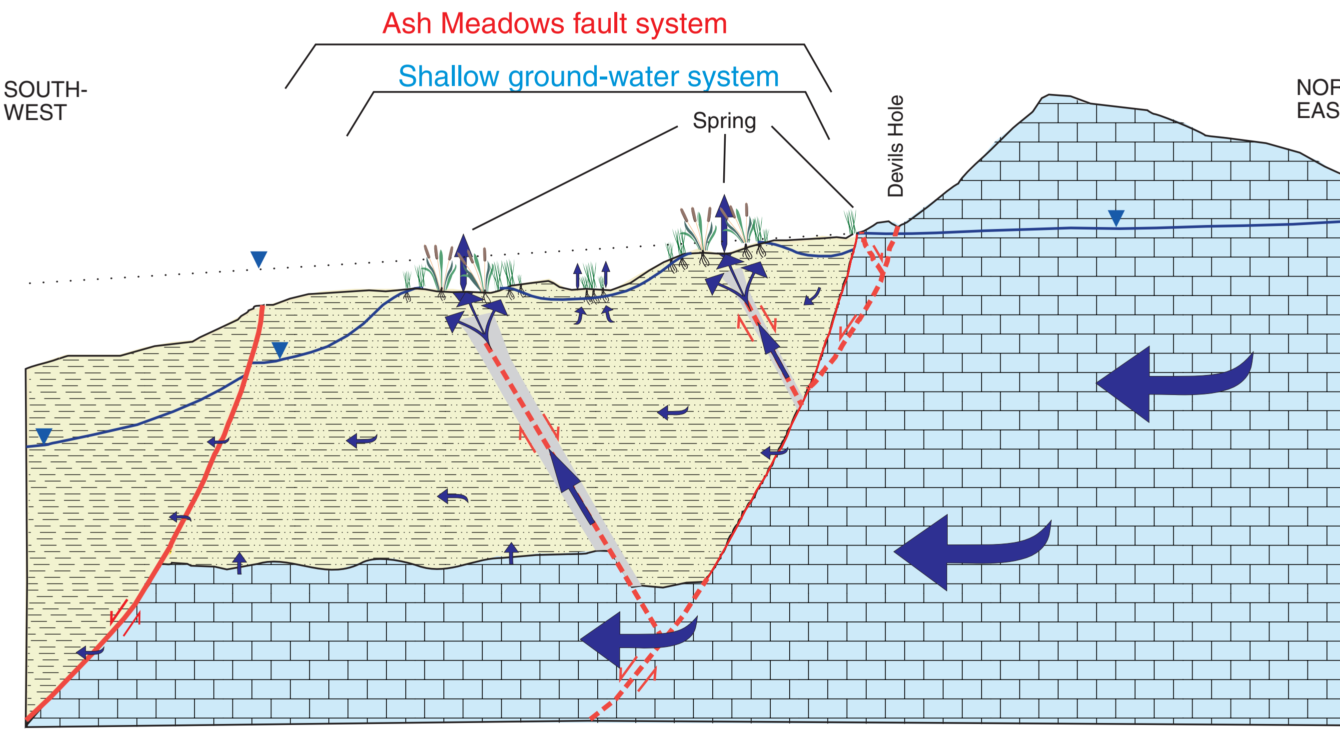
General Hydrology

The abundance of water available to the Ash Meadows area, when compared with that of other desert environments, is attributable to the area's unique hydrogeology (Winograd and Thordarson, 1975; Dudley and Larson, 1976). The many springs and shallow water table of the area are maintained primarily by ground water that moves into the area from the north and northeast through thick, semi-continuous rock units composed of fractured limestone and dolomite (figs. 2, 3, and 4). Together these carbonate-rock units make up what is referred to as the "regional carbonate-rock aquifer" (Dettinger and others, 1995; Prudic and others, 1995). Ground water moving through this aquifer originates from precipitation falling on the higher mountain ranges and mesas throughout an area that extends hundreds of miles to the north and east (Winograd and Thordarson, 1975; Waddell and others, 1984; Laczniak and others, 1996). Throughout much of the area between Ash Meadows and the highlands at which the water originates, the carbonate-rock units carrying most of the ground water are buried by thick accumulations of basin fill, and the water table typically is several hundred to several thousand feet below the land surface. Along this journey, ground water moves primarily through interconnected fractures, possibly dissolving some of the host carbonate rock and enhancing the pathways through which it flows. Ground water approaching Ash Meadows from the northeast is thought to be channeled between two occurrences of impermeable rock (Winograd and Pearson, 1976)—one beneath the northwestern part of the Spring Mountains and the other beneath the western part of the Specter Range (fig. 2).

Upon entering Ash Meadows, ground-water flow is impeded by the presence of one or more buried faults that down drop the bedrock block (carbonate?) underlying that part of the Amargosa Desert valley beneath and west of Ash Meadows (figs. 2-4). Collectively, these faults are referred to as the Ash Meadows fault system (previously termed the "gravity" fault by Winograd and Thordarson, 1975, pl. 1). The contrast in water-transmitting properties between the more permeable faulted and fractured carbonate rock and the juxtaposed, less permeable lacustrine, palustrine, and alluvial valley-fill deposits hinders southwestwardly flowing ground water forcing it upward to the surface (Winograd and Thordarson, 1975, p. 82). Some of the water being pushed upward from the regional carbonate-rock aquifer discharges from springs emerging directly from faults in the bedrock along the margins of some of the carbonate ridges. Some of the water discharges from springs emerging from alluvium, which likely are fed by water from or associated with faults in the underlying carbonate bedrock (fig. 4). The remainder of the water in the regional carbonate-rock aquifer beneath Ash Meadows either seeps slowly upward into the alluvial cover or continues flowing southwestward as underflow across the Ash Meadows fault system into the central part of the Amargosa Desert.

GROUND-WATER DISCHARGE

Ground water leaves the Ash Meadows area by four major processes: (1) springflow, (2) transpiration by local vegetation, (3) evaporation from soil and open water, and (4) subsurface outflow. Another process, although unnatural, by which ground water has been removed from the system is through pumping for local water supply. Since the early 1980's, pumping from the local area is minimal. Of all these processes, springflow is the most visible form of discharge (see section "General Hydrogeology," fig. 4). As ground water



Not to scale, vertical greatly exaggerated.

EXPLANATION

Alluvium—Valley-fill aquifer/confining unit

Limestone and dolomite—Regional carbonate-rock aquifer

Spring flow zone—Upward flow zone developed along and contemporary with growth faults

Fault— Arrow indicates direction of relative fault movement. Solid where fault forms barrier to lateral flow from carbonate-rock aquifer. Dashed where fault forms conduit for upward flow in valley-fill aquifer

Water table—Defines upper bound of valley-fill and carbonate-rock aquifers

Potentiometric surface of regional carbonate-rock aquifer

Area of evapotranspiration—Height of vegetation indicates relative quantity of transpiration. Length of arrow indicates relative quantity of evaporation

General direction of ground-water flow—Size of arrow indicates relative magnitude of ground-water flow

Figure 4. Generalized cross section showing local hydrologic and geologic features controlling ground-water flow in Ash Meadows area, Nevada. (Section generalized from Winograd and Thordarson, 1975; Dudley and Larson, 1976; Laczniak and others, 1996).

emerges from the orifices of the many springs scattered about the area, it either is pooled or is channeled into free-flowing drainages or local reservoirs. Once at the surface, water evaporates into the atmosphere or disperses outward and downward into the valley-fill deposits. Little if any surface water flows beyond the boundaries of Ash Meadows except during short periods (less than a few days) following occasional, intense rainfall.

Most of the spring and surface flow percolating downward into the valley-fill deposits recharges a shallow ground-water system (fig. 4). This flow system, referred to as the valley-fill aquifer, is bounded on top by a shallow water table and below by underlying carbonate bedrock. In addition to recharge from above, this aquifer also is recharged from below by diffuse upward flow from the underlying regional carbonate-rock aquifer. Other than the occasional influx of water from rainfall, these two sources of recharge provide most of the water maintaining the shallow, valley-fill aquifer. As with the regional carbonate-rock aquifer, some portion of ground water is likely to move southwestward across the Ash Meadows fault system and into the adjacent valley-fill deposits in the central part of the Amargosa Desert. Subsurface outflow is likely to be small owing to the relatively low permeability of adjacent valley-fill deposits. The remainder of the water is stored locally within the valley-fill aquifer, and in areas where the water table is at or near the surface, becomes available for use by plants and is exposed to atmospheric processes. Water evaporated directly from the plant structure is called transpiration and that evaporated from the soil structure is bare soil evaporation. Together these terms are referred to as evapotranspiration or ET. Evapotranspiration is the primary process by which ground water is removed from the valley-fill aquifer. Temporal differences in the relative amounts of water entering and leaving the valley-fill aquifer are indicated by changes in the water table. If more water enters than leaves the aquifer, the water table rises; and conversely, if more water leaves than enters, the water table falls. Seasonal changes in ET are responsible for the large seasonal fluctuations in the local water table—generally a declining water table in the summer and fall, and a rising water table in the winter and spring.

Most previous attempts to quantify ground-water discharge from Ash Meadows have been based primarily on measurements of springflow. Long-term annual estimates of ground-water discharge range between 16,500 and 17,500 acre-ft (Walker and Eakin, 1963; Winograd and Thordarson, 1975, p. 84; Dudley and Larson, 1976, p. 12). Although these "springflow" based estimates of ground-water discharge account for most of the water discharging by way of springs, the approach does not account for inflow to the valley-fill aquifer by subsurface seeps or by diffuse upward flow from below, across the surface of the underlying carbonate-rock aquifer. Assuming that subsurface outflow is small, one alternate method of estimating the loss of ground water from the Ash Meadows area is to quantify local ET from the general areas of ground-water discharge. An estimate of ET includes water losses from the regional carbonate-rock aquifer both by diffuse upward flow into the shallow valley-fill aquifer and by spring discharge. The ET estimate includes spring discharge because most springflow is evaporated or recycled back into the subsurface where it recharges the shallow valley-fill aquifer and eventually either is evaporated or transpired by the local vegetation.

Past estimates of ET from Ash Meadows were completed as part of regional assessments of the ground-water resource. Long-term annual ET estimates were computed from generalized delineations of phreatophyte growths and adaptations of annual ET rates for similar plant assemblages found throughout the western United States (Lee, 1912; White, 1932; Young and Blaney, 1942). Applying generalized acreages and ET rates, Walker and Eakin (1963, p. 22) estimated 24,000 acre-ft of annual ET over the entire Amargosa Desert. Of this total, about 10,500 acre-ft was determined to be from Ash Meadows (Winograd and Thordarson, 1975, p. 84); and the remainder from other smaller areas of ground-water discharge found throughout the Amargosa Desert. By comparing springflow and ET estimates, Winograd and Thordarson (1975, p. 84) suggest that ground water lost through transpiration by phreatophytes and evaporation from bare soil may be derived entirely from recycled springflow—but also discuss the likelihood of upward flow from the underlying carbonate-rock aquifer as being a source of the water supporting the area's phreatophyte population. These authors explicitly state that this quandary can only be resolved with a detailed study of evapotranspiration. This recommendation, the significance of quantifying ground-water discharge in terms of formulating an understanding of ground-water flow, and results from recent studies (Johnson, 1993; Nichols and others, 1997) suggesting that ET rates for local phreatophytes may be higher than those given in Walker and Eakin (1963, p. 23), provided the motivation to initiate a study to re-evaluate and more rigorously quantify ET from the Ash Meadows area.

This study of ET at Ash Meadows accounts only for ground water lost to the atmosphere. The estimates given do not account for ground water consumed at the refuge for operational needs, by the few local residents for domestic purposes, or by the local wildlife; or that which escapes the area as subsurface outflow. Currently, consumed water is minimal and probably does not exceed more than 10 acre-ft/yr. Previous estimates of subsurface outflow vary and range from zero to less than a few hundred acre-feet annually (Czarnecki and Waddell, 1984, table 1; Prudic and others, 1995, p. 62). The inclusion of these minor discharge components in the overall ground-water discharge estimate would likely be only a small fraction of the total. The estimation of these components is beyond the scope of this particular effort.

Quantification of Evapotranspiration

The basic method used to quantify evapotranspiration from the Ash Meadows area is similar to the approach applied previously by Walker and Eakin (1963). The methodology assumes that total ET can be quantified by summing individual estimates of annual ET computed for areas of similar plant (type and density) and soil (type and moisture content) cover. Hereafter, these areas of similar vegetation and soil conditions are referred to as ET units. An estimate of annual evapotranspiration for each ET unit is computed by multiplying the unit's acreage by an appropriate estimate of ET for the unit's vegetation and soil conditions. The major difference between previous estimates and the estimate presented in this study is in the specific techniques used to identify individual ET units, determine their spatial distribution, and estimate their associated ET rates. The techniques applied in this study take advantage of more modern technologies and are expected to result in a more accurate characterization. Previous methods defined and delineated ET units and their associated acreage on the basis of fairly generalized vegetation and soil mapping; whereas this study refines this approach by utilizing satellite imagery and remote sensing techniques. Evapotranspiration rates estimated in previous studies were based on measurements made for similar phreatophytes found at locations outside the study area; whereas this study made direct measurements of ET at locations within Ash Meadows. Because local vegetation and soil conditions in the Ash Meadows area are largely a consequence of the availability of ground water, water levels also were measured to define the depth and annual fluctuation of the water table.

Evapotranspiration Units

Evapotranspiration (ET) units were identified and mapped in the Ash Meadows area through a procedure by which spatial changes in vegetation and soil conditions were determined by classifying remotely sensed spectral data on the basis of similarities and patterns in spectral-reflectance characteristics. The procedure used Landsat Thematic Mapper (TM) imagery as the primary source of spectral data (fig. 5). TM imagery is acquired by satellites equipped with sensors that collect spectral information. The satellite measures 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, near infrared, and short wave infrared regions (fig. 6*A*). A seventh band, TM channel 6, measures thermal energy emitted from the surface of the Earth in the thermal infrared region, and is not used in this procedure.

Spectral data received by the satellite sensors are transmitted to earth as digital numbers, each denoting the reflectance of the wavelengths within a TM channel from a small area of the earth's surface. 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 these pixels define the spatial resolution of the imagery. One major benefit of these digital data sets or images is that they can be manipulated, processed, and geographically referenced using sophisticated computer algorithms.

Satellite data have long been used for identification and delineation of 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).

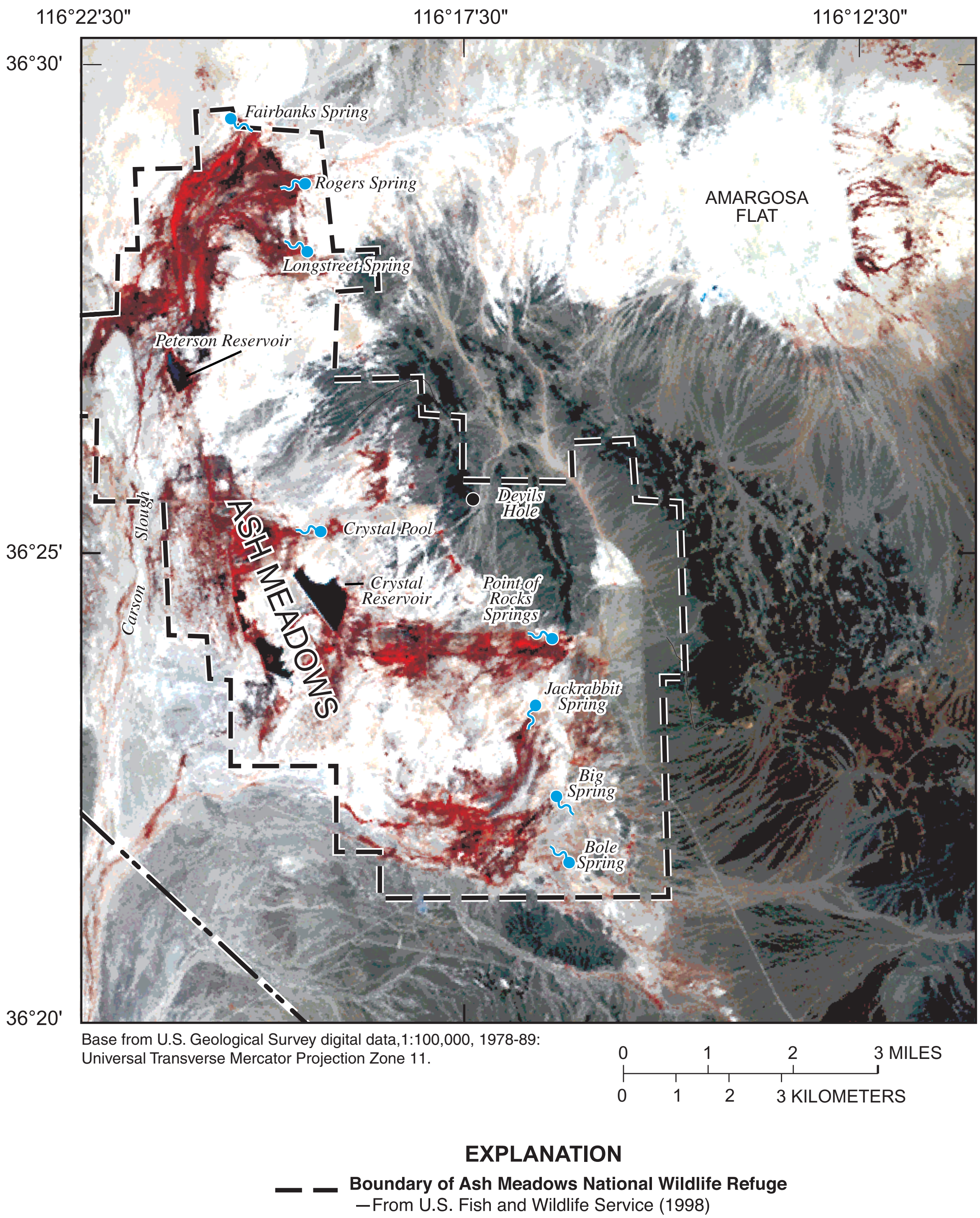


Figure 5. Color infrared composite generated from June 13, 1992, thematic mapper image, Ash Meadows area, Nevada (scene identification number LT5040035009216510).

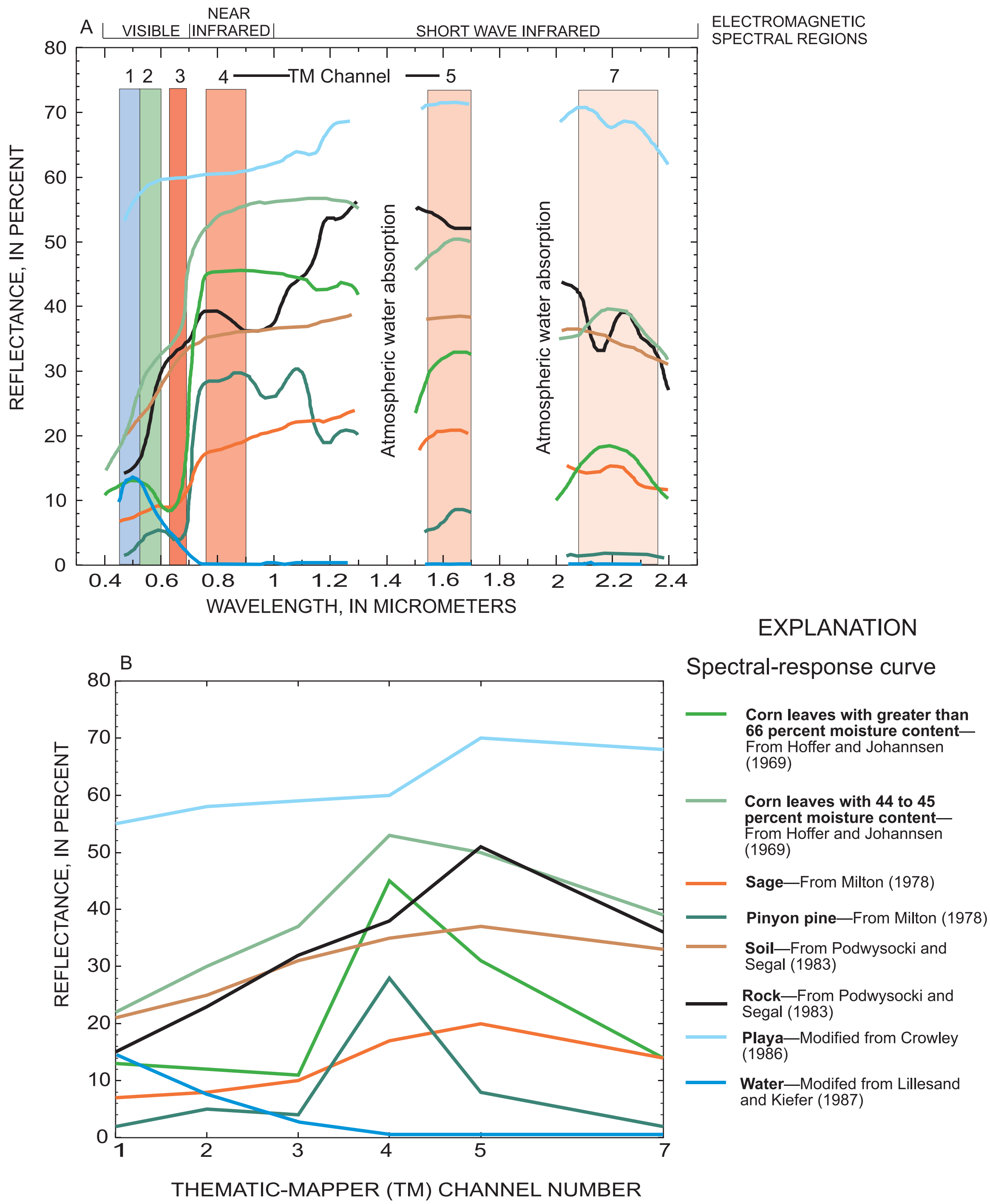


Figure 6. Spectral-response curves for land covers of different vegetation and soil conditions: *(A)* Continuous field or laboratory derived reflectance, *(B)* reflectance as developed for thematic map channels 1,2,3,4,5, and 7.

A closer analysis of 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, and 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 conditions—in general, the denser and more healthy the vegetation or the wetter the soil, the greater the rate of evapotranspiration (Ustin, 1992; William D. Nichols, U.S. Geological Survey, written commun., 1998). The procedure used to identify and map the ET units in the Ash Meadows area takes advantage of this relation and the characteristic patterns inherent in the spectral-response curves of differing vegetation and soil covers, particularly those associated with the evapotranspiration of ground water.

Spectral 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 each different land cover defines a unique class. The procedure presented here ultimately groups pixels into specific ET units, and thus is referred to as an ET-unit classification. The procedure independently classified two TM images of the Ash Meadows area into land covers representing the different vegetation and soil conditions likely to be associated with areas of ongoing ground-water ET. The dual classifications accounted for changes in vegetation and soil conditions occurring through a typical year. One image, taken June 13, 1992 (scene identification number LT5040035009216510, fig. 5), represents conditions of near maximum plant vigor and of high moisture, a period when the water table was near its highest level. The other image, taken September 1, 1992 (LT5040035009224510), represents conditions of high plant stress (dormancy) and of low moisture, a period when the water table was at or near its lowest level. The two classified images were combined to formulate a single map defining the spatial distribution of ET units throughout the Ash Meadows area (pl. 1).

The first step in classifying ET units was to determine the basic vegetation and soil conditions associated with each pixel in the imagery. The procedure applied a multi-spectral, maximum-likelihood classification using an unsupervised approach (Lillesand and Kiefer, 1987, p. 685-689). The unsupervised approach identifies the unique spectral responses present within the imagery as defined by TM channels 1, 2, 3, 4, 5, and 7. The approach determines the number of unique spectral-response curves within each image. Uniqueness is based on statistical similarities between reflectance values in the TM channels of individual pixels. Each curve is defined by statistical variables representing a unique set of reflectance values. An example comparing the spectral response or signature of different vegetation and soil conditions is shown in figure 6*A*. These same spectral signatures as developed from percent reflectance for the TM channels analyzed are shown in figure 6*B*.

Next, the procedure determined the spectral-response curve that best represented each pixel in the June and September imagery. The determination was made using the maximum likelihood classification technique. This technique compares reflectance values of each pixel against the signature defined by each spectral-response curve and calculates the statistical probability of a pixel being represented by each of the different spectral-response curves. Each pixel was assigned the number of the spectral-response curve having the greatest probability.

The next step in the process was to group spectral-response curves into clusters defining general vegetation and soil conditions. Spectral-response curves were grouped on the basis of similarities in the statistics defining their reflectance values. Each individual group is referred to as a spectral cluster and is discriminated by characteristic patterns described in the response of the cluster's reflectance values. Patterns are distinguished by differences in a spectral-response curve's slope between TM channels, or by sharp dips in the curve indicating absorption at a particular TM channel. The spectral signatures characteristic of pixels falling within areas dominated by open water, phreatophytes, and moist bare soils were used to define six spectral clusters representing the different vegetation and soil conditions consistent with likely areas of ground-water evapotranspiration. In addition to these six spectral clusters, the signatures characteristic of pixels falling in areas dominated by sparse upland desert vegetation or in xeric habitats were used to define the spectral cluster representing areas of no substantial ground-water ET. Each cluster was given a number to digitally differentiate each of the conditions of interest. A description of each of the seven general land-cover clusters (and one unclassified area) is given in table 1. The spectral clusters defining the six different vegetation and soil conditions representing likely areas of substantial ground-water ET are shown in figure 7 for the June and September imagery.

Open water was determined independently for both dates from an August 8, 1993, SPOT (*Systeme Probatoire d'Observation de la Terre*) image. SPOT imagery provides spectral data at a much finer spatial resolution (about 60 ft by 60 ft) than TM imagery but contains spectral information only in the visible and near infrared regions of the electromagnetic spectrum. SPOT imagery lends itself well to discriminating open water, but was found to be less effective in discriminating land covers representative of ET units throughout the Ash Meadows area.

The final step in the ET-unit classification combined the two independently classified images into a single digital image defining ET units and their spatial distribution. The cluster combinations resulting from combining the June and September classifications provided the basis for assigning and identifying ET units. The number of pixels assigned to each cluster combination is shown in table 2. In this table, rows identify the number of pixels assigned to each spectral cluster by the June classification, and columns identify the number of pixels assigned to each spectral cluster by the September classification. For example, a value of "2" in the third row (cluster 2) and the second column (cluster 1) indicates that only two pixels were classified as cluster 2 from the June imagery and cluster 1 from the September imagery.

The spatial resolution of pixels given in table 2 is much finer than that of the original TM imagery. The finer resolution was attained by re-sampling the original images at a pixel spacing of about 60 ft by 60 ft. The re-sampling does not provide more spatial detail but allowed for the direct integration of the TM and SPOT imagery (which was used to classify open-water bodies).

The major differences between the June and September classifications are apparent when comparing cluster combinations defined by the row and column values in table 2. If the two classifications were identical, all non-bolded elements in table 2 would be zero. The sum of the integer values in the non-bolded elements indicates the number of pixels assigned to different ET units by the two classifications. Some of the differences can be attributed to errors in the image registration, but most are likely to be the result of changing vegetation and soil-moisture conditions between the time of year during which the images were acquired. Most differences noted in the table can be explained in

Table 1. Land covers represented by spectral clusters identified in June and September 1992 thematic mapper imagery of Ash Meadows area, Nevada

Cluster number [1]	Description of land cover
0	Area of no substantial ground-water evapotranspiration (unclassified).
1	Area dominated by submerged aquatic vegetation and open-water marsh; water above land surface.
2	Area dominated by dense vegetation; forest or grass/shrub meadows; water table below land surface; soils moist to dry.
3	Area dominated by dense to moderately dense vegetation; mature grasslands, intermittently flooded; water table at or near land surface; soils wet to moist.
4	Area dominated by sparse vegetation; open grass and shrub lands; water table below land surface; soils dry.
5	Area dominated by moist bare soil; vegetation very sparse; water table at or near land surface; soils wet to moist.
6	Previously farmed field; vegetation sparse; water table below land surface; soils dry.
7	Area of open water; reservoir or large spring pool.

[1] Spectral-response curves for clusters 1, 2, 3, 4, 5, and 6 shown on figure 7.

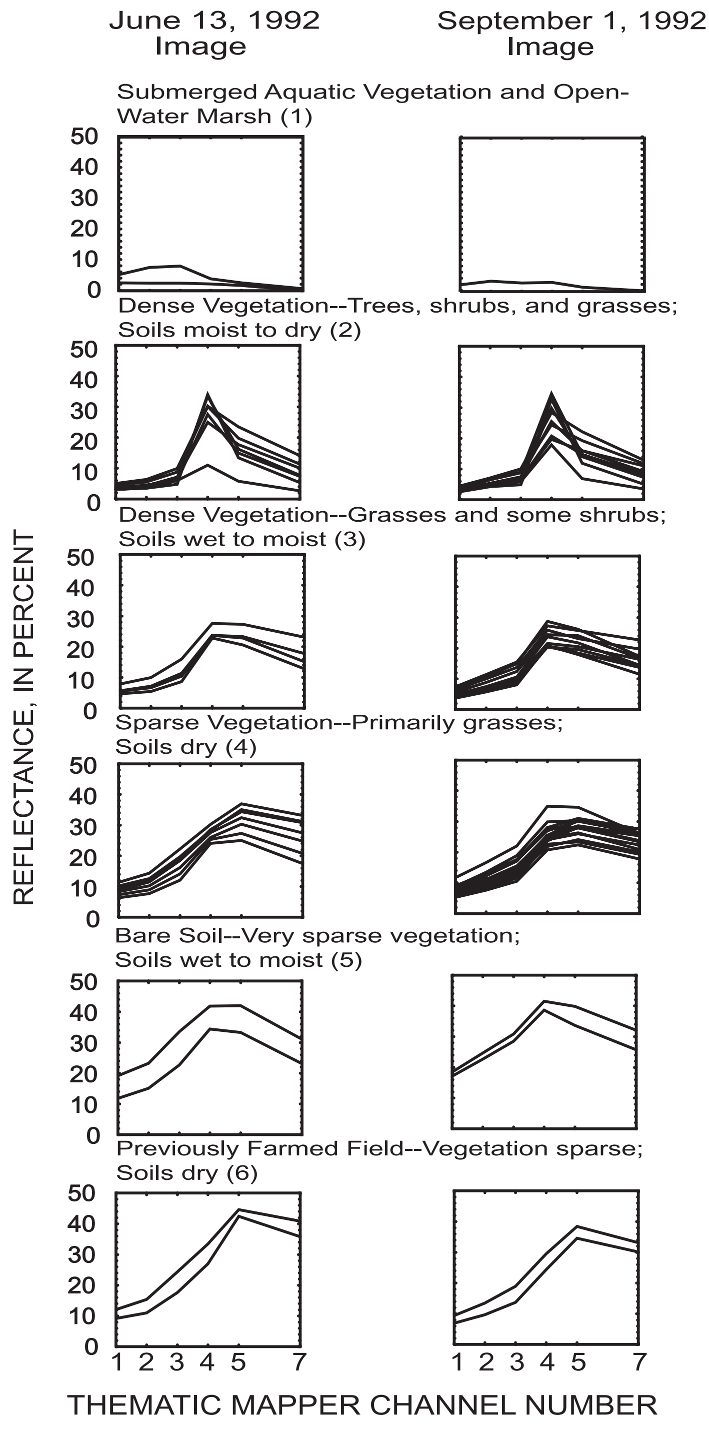


Figure 7. Spectral clusters and component spectral-response curves used in June and September 1992 image classifications for land covers of different vegetation and soil conditions equated with ground-water evapotranspiration in Ash Meadows area, Nevada. Integer in parenthesis is cluster number (table 1).

Table 2. Pixel classification for combined June and September 1992 thematic mapper imagery of Ash Meadows area, Nevada

[Integer in each cluster row and column position is number of pixels making up cluster combination. Integer given as total is total number of pixels making up cluster. Pixel size is about 60 feet by 60 feet. General description of vegetation and soil conditions for each cluster given in table 1. Bolded diagonal identifies number of pixels assigned to same cluster in June and September classifications.]

		September 1, 1992, image								June total
	Cluster	0	1	2	3	4	5	6	7	
June 13, 1992, image	0	**1,141,653**	0	47	716	15,899	1,461	770	0	1,160,546
	1	201	**121**	469	118	193	4	14	0	1,120
	2	31	2	**5,521**	965	564	0	1	0	7,084
	3	31	0	4,045	**3,866**	1,634	2	0	0	9,578
	4	21,232	4	2,920	9,164	**45,533**	5	367	0	79,225
	5	2,457	2	86	1,025	2,798	**449**	4	0	6,821
	6	4,182	0	7	57	933	0	**1,244**	0	6,423
	7	0	0	0	0	0	0	0	**1,972**	1,972
September total		1,169,787	129	13,095	15,911	67,554	1,921	2,400	1,972	1,272,769

terms of expected seasonal changes. For example, the greater number of pixels assigned to non-zero clusters by the June classification implies a larger area of ground-water ET. This implication is consistent with field observations that indicate a greater availability of accessible ground water and more vigorous plant growth in June than in September. The one exception to this overall trend is the large number (15,899) of pixels classified as sparse vegetation (cluster 4) in the September image and as areas of no substantial ground-water ET (cluster 0) in the June image (table 2). This inconsistency arises by the omission of a few spectral-response curves from cluster 4 in the June classification. These spectral-response curves were omitted purposely because, if included, would classify vegetation dominated by non-phreatophytic species (such as saltbush and desert holly) as areas of ground-water ET (cluster 4). Instead, the September classification was used to define the outer boundary of sparse phreatophyitic vegetation. Classification of areas dominated by non-phreatophytic plant species based on the June imagery can be explained by the vigor of these species during late spring and early summer.

Each cluster combination was evaluated on the basis of field observations and its spectral-reflectance characteristics. The evaluation process identified seven ET units (table 3) that preserved the general spectral and physical characteristics of the original land-cover designations (table 1), with two exceptions. One difference was that class 4 (sparse vegetation, table 1) and class 6 (previously farmed field, table 1) were combined into one unit (SGV, table 3) on the basis of similarities in vegetation, general soil conditions, and depth to water. The other major difference was the creation of a unit to discriminate areas of dense wetland vegetation (DWV, table 3). The reclassification scheme used to assign an ET unit to each pixel is given in table 4. In this table, rows represent cluster classifications as determined from the June imagery, and columns represent cluster classifications determined from the September imagery. The ET-unit designator (described in table 3) given for each cluster (row, column) combination is the ET unit that was assigned to each pixel on the basis of both the June and September classifications. For example, the ET-unit designator SAV (submerged aquatic vegetation) assigned to the cluster combination (2,1) implies that all pixels classified as cluster 2 from the June imagery and cluster 1 from the September imagery (table 2) were reclassified as SAV.

After being reclassified, the image was smoothed using a nominal filter. In general, the filter replaced spurious classified pixels (areas defined by less than three adjacent pixels) in the image and filled single-pixel gaps within delineated ET areas by assigning them to the ET unit most representative of its neighbors. The final map delineates 10,352 acres of ongoing ET in the Ash Meadows area. The acreage and spatial distribution of individual ET units are given in plate 1. The largest ET unit, defined as sparse grassland vegetation, covers 7,160 acres; whereas the smallest ET unit, defined as submerged aquatic vegetation, covers only 81 acres.

Table 3. Evapotranspiration (ET) units determined from spectral-cluster combinations for Ash Meadows area, Nevada

ET-unit identifier	Cluster combination [1]	General description of ET unit	Abbreviated ET unit description [2]
UCL	(0,0)	Area of no substantial ground-water evapotranspiration (unclassified).	Unclassified
OWB	(7,7)	Area of open water; reservoir or large spring pool.	Open-water body
SAV	(1,0) (1,1) (1,2) (1,3) (1,4) (1,5) (1,6) (2,1) (4,1)	Area dominated by submerged aquatic vegetation and open-water marsh; shallow part of open water bodies; perennially flooded; water above surface. Includes area of sparse emergent vegetation.	Submerged aquatic vegetation
DWV	(3,2) (3,3)	Area dominated by dense wetland vegetation, primarily tall reedy and rushy marsh plants; perennially flooded; water at or above surface.	Dense wetland vegetation
DMV	(0,2) (2,0) (2,2) (2,3) (2,6)	Area dominated by dense meadow vegetation, primarily trees, mixed trees and grasses, or mixed grasses and shrubs; water table below land surface; soils moist to dry.	Dense meadow vegetation
DGV	(0,3) (2,4) (3,0) (3,4) (4,2) (4,3) (5,2) (5,3)	Area dominated by dense to moderately dense grassland vegetation, primarily grasses, short rushes, and occasional scattered trees and shrubs; intermittently flooded; water at or near land surface; soils wet to moist.	Dense grassland vegetation
SGV	(0,4) (0,6) (4,0) (4,4) (4,6) (6,0) (6,2) (6,3) (6,4) (6,6)	Area dominated by sparse grassland vegetation; primarily grasses; water table below land surface; soils dry.	Sparse grassland vegetation
MBS	(0,5) (3,5) (4,5) (5,0) (5,1) (5,4) (5,5) (5,6)	Area dominated by moist bare soil; vegetation very sparse, primarily grasses; intermittently flooded, water table near or below land surface; soils moist.	Moist bare soil

[1] First integer in parenthesis is June cluster number (row in tables 2 and 4), second integer is September cluster number (column in tables 2 and 4).

[2] Matches description given in explanation of plates 1 and 2.

Table 4. Reclassification scheme used to assign evapotranspiration (ET) units from cluster combinations developed by combining June and September 1992 classifications of Ash Meadows area, Nevada

[Character string (acronym) in cluster row and column position identifies ET unit for given cluster combination. Cluster combinations are developed from independent classifications of June and September 1992 thematic mapper imagery. Classes are described in table 1. Double dash indicates that no pixels had cluster combination (table 2). ET units are described in table 3.]

		ET-unit identifier							
		September 1, 1992, image							
	Cluster	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
June 13, 1992, image	**0**	UCL	--	DMV	DGV	SGV	MBS	SGV	--
	1	SAV	SAV	SAV	SAV	SAV	SAV	SAV	--
	2	DMV	SAV	DMV	DMV	DGV	--	DMV	--
	3	DGV	--	DMV	DMV	DGV	MBS	--	--
	4	SGV	SAV	DGV	DGV	SGV	MBS	SGV	--
	5	MBS	MBS	DGV	DGV	MBS	MBS	MBS	--
	6	SGV	--	SGV	SGV	SGV	--	SGV	--
	7	--	--	--	--	--	--	--	OWB

Accuracy Assessment

The ET units, as defined and delineated, are not intended to be exact but rather generalizations of the long-term average conditions. The accuracy of the final ET-unit classification is difficult to assess because the vegetation and soil conditions throughout the Ash Meadows area are not homogeneous, and transitions from one condition to the next are not abrupt but rather subtle and often occur over broad zones. Another factor contributing to the difficulty in assessing the accuracy of mapped ET units is that the vegetation and soil conditions change during a year and from year to year. Despite these difficulties, an assessment of the overall accuracy was made of the ET-unit classification.

The overall accuracy of the final ET-unit map (pl. 1) was assessed by comparing units assigned on the basis of field observation with those assigned by the classification procedure. Comparisons were made at 30 sites. Each ET-unit was represented by at least one site in the assessment. Assessment locations included the sites established to measure ET rates (pl. 1). A field observation included one or more site visits to examine and document actual site conditions. Each site was described, photographed, and later evaluated and assigned to one of the seven ET-units independently by two individuals. The few discrepancies in class assignments were resolved through discussion and site re-visitation.

The overall performance or accuracy of a classification procedure can be described in terms of the percentage of sites classified correctly (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. An assessment of the accuracy of the final ET-unit classification is presented as a contingency table (table 5). The table shows the number of sites assigned to each ET unit by field observation (row) and by classification (column). The value “14” given in the row-column combination of SGV (sparse grassland vegetation) in table 5 indicates that 14 of the evaluated sites were assigned to SGV (sparse grassland vegetation) both by field observation and by classification. The three values of “1” in this same row indicate that three additional sites were assigned to SGV by field observation but were assigned incorrectly to DWV (dense wetland vegetation), DMV (dense meadow vegetation), and DGV (dense grassland vegetation) by classification. On the basis of this example, 14 of the 17 sites assigned to SGV by field observation also were assigned by classification to SGV for an accuracy of 82 percent. The performance of the classification procedure for individual ET units ranged from 67 to 100 percent (table 5). The overall performance of the assessment is 86.6 percent, where performance is defined as the ratio of the number of sites assigned correctly by classification (26) to the total number of sites evaluated (30). This performance is within the acceptable limit (85 percent or greater) established by Anderson and others (1976, p. 5).

Table 5 indicates that the lowest performing class is dense meadow vegetation (DMV, table 3). The low performance of this class could be related to the limited number of sites evaluated (3), or rather may be attributed to the class being comprised largely of mixed

Table 5. Accuracy assessment of evapotranspiration (ET)-unit classification for Ash Meadows area, Nevada

[ET units are described in table 3.]

	ET-unit identifier	Number of sites assigned by classification						Number of sites evaluated	Percent correct
		SAV	DWV	DMV	DGV	SGV	MBS		
Number of sites assigned by field observation	SAV	1	0	0	0	0	0	1	100
	DWV	0	5	0	0	0	0	5	100
	DMV	0	1	2	0	0	0	3	67
	DGV	0	0	0	3	0	0	3	100
	SGV	0	1	1	1	14	0	17	82
	MBS	0	0	0	0	0	1	1	100
Total		1	7	3	4	14	1	30	

vegetation covers—trees, shrubs, and grasses. The mixed and differing vegetation associated within this class yield a less distinctly defined spectral cluster (fig. 7, cluster 2) making its classification more ambiguous. The discrepancy between the observed and classified site assignments is considered acceptable because both procedures assigned the site in question to a unit of dense vegetation—dense wetland vegetation (DWV) by classification and dense meadows vegetation (DMV) by observation. The average of the individual class performances is 91.5 percent (table 5), also suggesting an acceptable ET-unit classification of the Ash Meadows area.

Evapotranspiration Rates

In most arid and semi-arid environments, water is scarce and vegetation sparse to nonexistent. Ash Meadows, although a desert community, abounds in water and vegetation relative to its surroundings. The water sustaining the vegetation, shallow water table, springs, and flowing drainage channels throughout the local area is derived almost entirely from ground water, much of which is lost to the atmosphere through ET. Evapotranspiration is a process by which water from the earth's surface is transferred to the atmosphere. The transfer requires that water change state from a liquid to a vapor, and in so doing it 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 many of the methods used to estimate ET.

Energy Budget Method

The energy at the surface of the earth can be described by the energy budget, which balances the incoming and outgoing energy fluxes. Assuming that energy terms related to biological processes and the storage of heat in the plant canopy are negligible, the energy budget for conditions typical of Ash Meadows can be expressed mathematically in terms of its principal component energy fluxes as

$$R_n = H + G + \lambda E \tag{1}$$

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. Net radiation can be expressed as

$$R_n = (R_{Si} - R_{So}) + (R_{Li} - R_{Lo}) \tag{2}$$

where R_{Si} is incoming short-wave radiation (energy per area per time);

R_{So} is outgoing short-wave radiation (energy per area per time);

R_{Li} is incoming long-wave radiation (energy per area per time); and

R_{Lo} is outgoing long-wave radiation (energy per area per time).

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. For soil, subsurface heat flux can be expressed as

$$G = HF_s + \{\delta T_s\, d_{bls}\, \rho_{Bs}\, [C_s + (\mathrm{W}\, C_w)]\} \tag{3}$$

where HF_s is heat flux through soil at some measurement depth (energy per area per time);

δT_s is change in soil temperature between surface and soil heat flux measurement depth per unit time (temperature per time);

d_{bls} is depth below land surface at which heat flux is measured (length);

ρ_{Bs} is bulk density of soil (mass per volume);

C_s is specific heat of dry soil (energy per temperature per mass);

W is gravimetric soil water content (dimensionless); and

C_w is specific heat of water (energy per temperature per mass);

and for water as

$$G = \delta T_w\, d_{bws}\, \rho_w\, C_w \tag{4}$$

where δT_w is change in water temperature per unit time (temperature per time);

d_{bws} is depth below water surface over which temperature is measured (length); and

ρ_w is density of water (mass per volume).

Net radiation and subsurface heat flux can be measured or computed in the field using readily available instrumentation. The difference between these two components is the energy available for sensible and latent heat flux at the earth's surface. Equation 1, which describes the energy budget as components of net radiation, can be rearranged as

$$E_a = H + \lambda E = R_n - G \qquad (5)$$

where E_a is available energy (energy per area per time).

Sensible heat flux (H), the energy that goes into heating the air, is proportional to the product of the temperature gradient and the turbulent transfer coefficient for heat, and can be expressed as

$$H = \rho_a C_a k_h dT/dz_t \qquad (6)$$

where ρ_a is density of air (mass per volume);
C_a is specific heat of air at a constant pressure (energy per mass per temperature);
k_h is turbulent transfer coefficient of heat in air (area per time); and
dT/dz_t is temperature gradient near the earth's surface, where T is temperature and z_t is height at which temperature is measured.

Latent heat flux (λE), which is the energy consumed for evapotranspiration and is proportional to the product of the vapor pressure gradient and the turbulent transfer coefficient for vapor, can be expressed as

$$\lambda E = (\lambda \rho_a \varepsilon k_v / P) de/dz_e \qquad (7)$$

where ε is ratio of molecular weight of water to dry air (dimensionless);
k_v is turbulent transfer coefficient of vapor (area per time);
P is ambient air (barometric) pressure (force per area); and
de/dz_e is vapor pressure gradient near the earth's surface, where e is vapor pressure (force per area) and z_e is height at which vapor pressure is measured.

Neither sensible (H) nor latent (λE) heat flux, as expressed in equations 6 and 7, can be determined directly unless the turbulent transfer coefficients are known. However, an indirect method for solving the energy budget equation was developed by Bowen (1926).

Rearranging equation 5, latent heat can be expressed as

$$\lambda E = E_a / [(H/\lambda E) + 1]. \qquad (8)$$

Bowen realized from this equation that if the turbulent transfer coefficients in equations 6 and 7 are equal, the ratio between sensible and latent heat flux can be expressed as

$$H/\lambda E = [(PC_a) / (\lambda \varepsilon)] [(dT/dz) / (de/dz)]. \qquad (9)$$

Recasting temperature and vapor pressure differentials as finite differences over two reference heights, equation 9 reduces to

$$H/\lambda E = [(PC_a) / (\lambda \varepsilon)] [(T_l - T_u) / (e_l - e_u)] \qquad (10)$$

where $T_{l,u}$ is temperature at lower or upper reference point; and
$e_{l,u}$ is vapor pressure at lower or upper reference point (force per area).

The ratio $(PC_a) / (\lambda \varepsilon)$ is referred to as the psychrometric constant (γ_c). The ratio is known to be nearly constant for a given altitude and can be approximated by a function of air pressure and temperature (Fritschen and Gay, 1979).

The ratio between the sensible and latent heat flux, $H/\lambda E$, as expressed in equation 10, has come to be known as the Bowen ratio (β). Substituting the Bowen ratio into equation 8, latent heat flux can be expressed as

$$\lambda E = E_a / \{\gamma_c [(T_l - T_u) / (e_l - e_u)] + 1\}. \qquad (11)$$

Evapotranspiration, the mass flux of water associated with the latent heat flux, can be expressed as

$$ET = \lambda E / (\lambda \rho_w) \qquad (12)$$

where ET is the rate of evapotranspiration (length per time).

Substituting equation 11 into equation 12, ET can be expressed as

$$E_a / (\lambda \rho_w) \{\gamma_c [(T_l - T_u) / (e_l - e_u)] + 1\} \qquad (13)$$

Knowing or assuming that:

(1) the vapor pressure (e) can be computed as a function of the relative humidity and saturated vapor pressure, which itself is a function of air temperature;

(2) the turbulent transfer coefficients for heat and vapor (k_h and k_v; eqns. 6 and 7, respectively) are nearly equal (Bowen, 1926);

(3) the density of water (ρ_w) is constant for the given pressure and temperature range; and

(4) the latent heat of vaporization varies weakly with temperature and can be determined by a function of air temperature,

ET can be readily calculated from measurable micrometeorological data. Equation 13 was solved with data measured in the field locally and provided the primary method by which evapotranspiration was estimated at selected locations throughout Ash Meadows.

Some conditions exist for which the Bowen ratio becomes unstable. One such condition is when the Bowen ratio approaches -1. When this occurs, the equation expressing latent heat as a function of the Bowen ratio (eq. 8) approaches infinity. This and other potential errors associated with applying the Bowen ratio to solve the energy budget are not discussed in this report but can be found in standard texts and in a paper by Ohmura (1982).

Other energy-budget formulations based on variations of Bowen ratio and energy-combination methods were used to validate and provide independent checks on estimates calculated by equation 13. In general, each of these formulations solve the energy budget by computing latent and sensible heat fluxes indirectly. This report does not provide the theoretical derivation of each of the formulations—instead interested readers are referred to their published sources (Monteith, 1973; Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990; Nichols, 1991, 1992; G.A. DeMeo, U.S. Geological Survey, written commun., 1998).

Site Selection and Instrumentation

Ten sites were selected and instrumented to measure ET from areas dominated by the different vegetation and soil conditions found throughout Ash Meadows. Other factors influencing the selection and location of a site were year-round accessibility and adequate fetch. Generally, fetch is defined as the distance between the sensor and the upwind edge of the environment of interest and 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 sites selected for instrumentation are given in table 6.

With one exception, sites were located such that each ET unit was represented by at least one site. The lone exception was the ET unit referred to as submerged aquatic vegetation (SAV, table 3). Although spectrally unique, SAV is only 81 acres and is assumed to evapotranspire water at a rate equal to that of open water (OWB, table 3). Multiple sites were located in certain units to evaluate the potential for differences in the rate of ET associated with intra-unit changes in vegetation or soil conditions. Three sites were located in the largest unit (7,160 acres, pl. 1) defined as sparse grassland vegetation (SGV). Two sites each were located within the units defined as dense grassland vegetation (DGV) and moist bare soil (MBS). Time constraints, accessibility issues, and instrumentation difficulties did not allow for the individual evaluation of every intra-unit change in vegetation or soil conditions.

Each site was equipped with the instrumentation required to measure or compute the micrometeorological data needed to calculate the energy-budget fluxes by the several methods discussed. A schematic showing the typical instrument arrangements used to determine ET over land and over water is shown in figure 8. Photographs of actual land and water-based installations are presented in figure 9. A typical land-based installation consists 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 sensors to measure soil and plant canopy temperatures; and a set of thermocouples and heat flux plates to compute soil heat flux (fig. 8). Instrument pairs are used to measure vertical differences of a particular variable between two reference heights. Initially, vapor-pressure gradients were computed from dew-point temperatures measured by pumping air from two reference heights through a single chilled-mirror hygrometer (Tanner and others, 1987). During the early part of the study, the hygrometer was found to be unreliable over extended time for many of the climatic conditions being measured. To remedy this problem, one of two modifications were made to the instrumentation. Either the chilled mirror hygrometer was replaced with a solid-state temperature/humidity probe or was replaced with individual temperature/humidity probes to measure relative humidity and temperature at two reference heights. In the two-probe setup, instrument positions were exchanged once during a data acquisition interval

Table 6. Location and general description of sites equipped with micrometeorological instruments and used to determine evapotranspiration (ET) from Ash Meadows area, Nevada

[Geographic coordinates given in degrees, minutes, seconds.]

Site name	Site identifier (pl. 1)	Latitude	Longitude	Altitude (feet above sea level)	Period of data acquisition	Description of dominant vegetation cover [1] and soil-moisture conditions [2]	ET-unit identifier [3]
Bole Spring North	BSNORT	362227	1161811	2,180	January 1996—September 1997	Sparse to very sparse cover of bunch grass; soil moisture varies from moist in winter to dry in summer	MBS
Bole Spring South	BSSOUT	362213	1161817	2,175	January 1996—September 1997	Sparse cover of saltgrass; surface periodically floods during late winter and early spring, otherwise soil moisture varies from moist in winter to very dry in summer	SGV
Carson Meadow	CMEADW	362517	1162023	2,171	March 1995—March 1997 [4]	Dense cover of mixed grasses, clover, and scattered shrubs; soil moisture varies from moist in winter to dry in summer	DMV
Fairbanks Meadow	FMEADW	362859	1162018	2,249	March 1997—September 1997 [5]	Dense cover of saltgrass; surface periodically floods during late winter, otherwise soil moisture varies from wet in winter to dry in summer	DGV
Fairbanks Swamp	FSWAMP	362901	1162022	2,248	March 1995—September 1997	Dense cover of cattails and reeds; surface flooded throughout year	DWV
Lower Crystal Flat	LCFLAT	362422	1162006	2,148	December 1995—June 1996	Very sparse cover of bunch grass; soil moisture varies from wet in winter to moist in summer	MBS
Peterson Reservoir	PRESVR	362644	1162105	2,169	April 1996—September 1997	Open-water body	OWB
Rogers Spring 1	RGSPR1	362853	1162005	2,256	December 1993—February 1996	Sparse to moderate cover of saltgrass; soil moisture varies from moist in winter to very dry in summer	SGV
Rogers Spring 2	RGSPR2	362855	1161955	2,253	December 1993—February 1996	Sparse to moderate cover of wire-grass and saltgrass; soil moisture varies from wet in winter to moist in summer	DGV
Spring Meadow	SMEADW	362538	1162120	2,139	June 1995—September 1997	Sparse to very sparse cover of saltgrass; soil moisture varies from dry in winter to very dry in summer	SGV

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

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

[3] ET units are described in table 3.

[4] Site was destroyed by fire and not replaced.

[5] Site still active at time of publication.

EXPLANATION

1. **Net radiation**—net radiometer
2. **Air temperature and relative humidity**—temperature/humidity probe
3. **Windspeed**—anemometer
4. **Soil-surface temperature**—infrared temperature sensor
5. **Canopy temperature**—infrared temperature sensor
6. **Water-surface temperature**—infrared temperature sensor
7. **Subsurface soil temperature**—thermocouple
8. **Soil heat flux**—heat flux plate (thermopile)
9. **Subsurface water temperature**—thermocouple

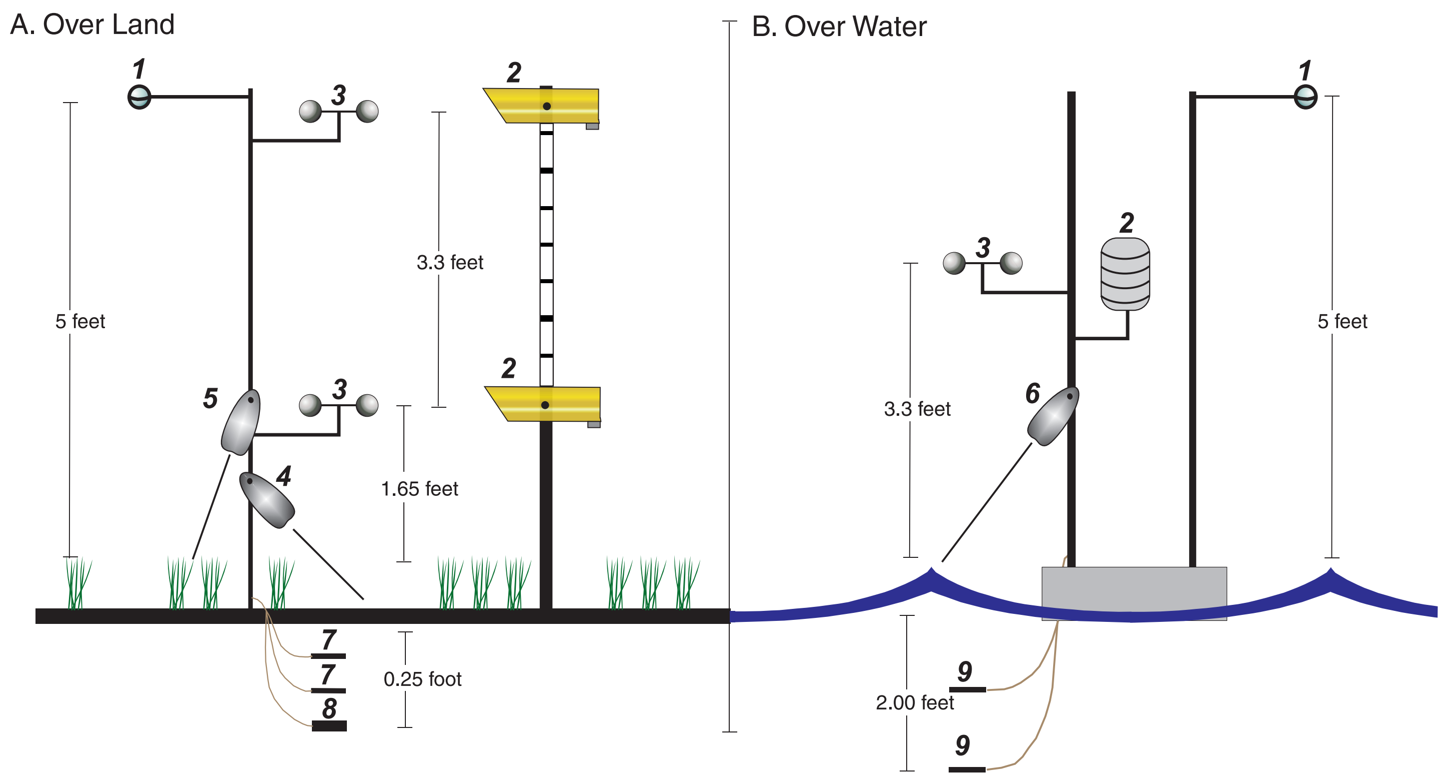


Figure 8. Schematic of instrumentation arrangements installed and used to measure micrometeorological data to determine evapotranspiration over *(A)* land and *(B)* water from Ash Meadows area, Nevada.

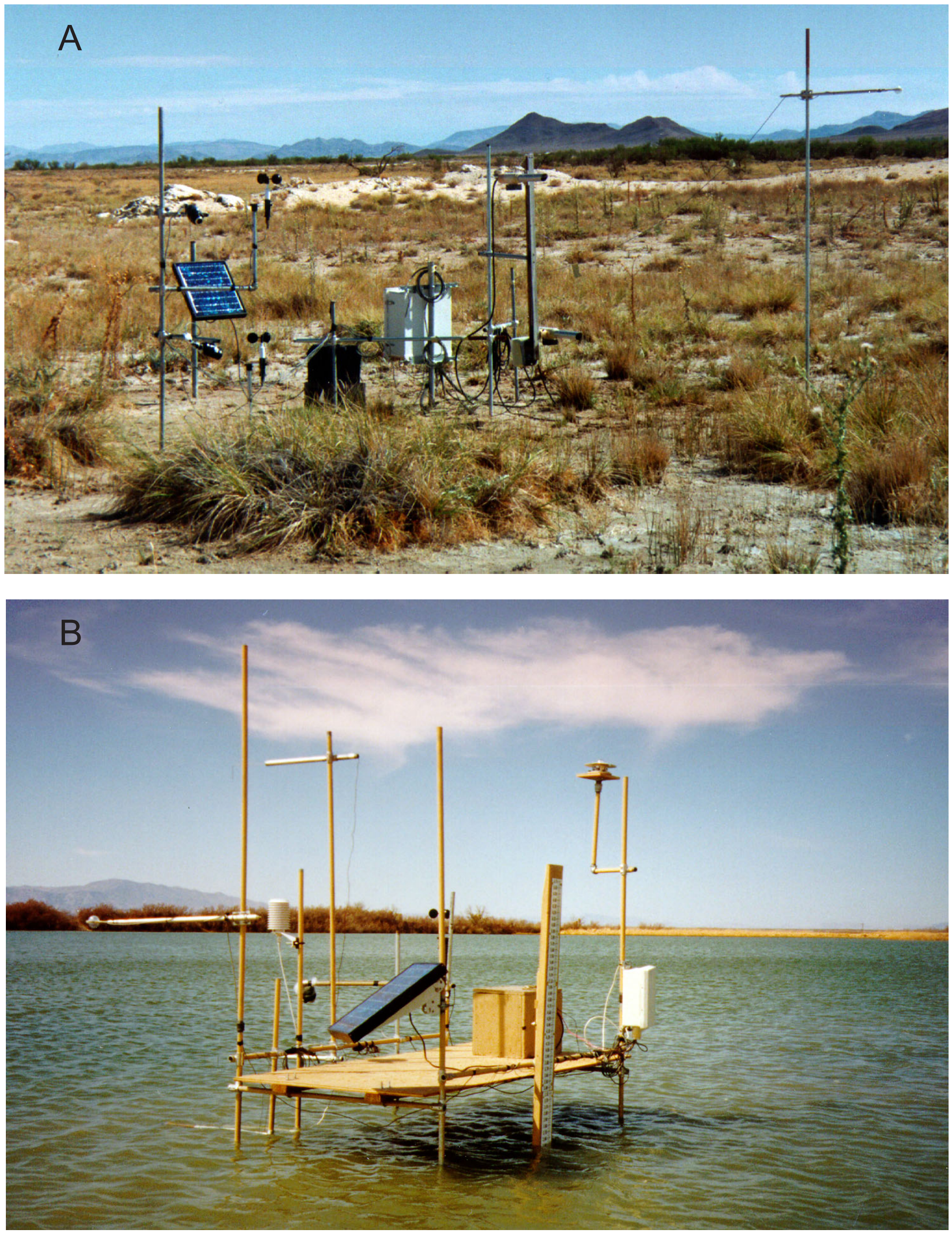


Figure 9. Typical instrument installations used to determine evapotranspiration (ET) from Ash Meadows area, Nevada. *(A)* LCFLAT site (pl. 1, table 6) established over moist bare soil (MBS, table 3). Vegetation is sparse and consists primarily of the bunchgrass, alkali sacaton (*Sporobulus airoides*). Soil is encrusted with thin layer of salt deposits. *(B)* PRESVR site established over open water (OWB, table 3).

(20 minutes) to cancel any bias that may exist between the individual probes (Fritschen and Simpson, 1989; Fritschen and Fritschen, 1993). Readers interested in additional discussion of the instrumentation applied in this study are referred to Nichols and Rapp (1996).

An ET site established over open water uses similar instrumentation but has a slightly different instrument arrangement (fig. 8). The major differences are related to the presence of water. For open water, the temperature and vapor pressure gradients are not measured between two reference heights in the air but rather between one reference height in the air and the water surface. Thus, only one temperature/humidity probe is required for air temperature and relative humidity measurements. Temperature at the water surface is measured with an infrared temperature transducer, and assuming that the air is saturated at the water surface, vapor pressure is computed as the saturation vapor pressure. Another difference affecting the general setup is that subsurface heat flux was not calculated with heat flux plates but rather using temperature probes set below the water surface to compute changes in heat storage (eq. 4). Heat-storage changes were computed only for the upper 2 ft of the water column and changes from greater depths were assumed insignificant to the overall energy budget.

Micrometeorological Data and Daily and Annual Evapotranspiration

Micrometeorological data required to solve the energy budget by the methods discussed previously were collected at each of the ET sites for a minimum of 1 year, which is considered the minimum period by which seasonal fluctuations in evapotranspiration rates can be evaluated and documented. Multiple years of data were acquired at some sites to assess annual changes in ET that may result from climate variations, such as differences between dry and wet years. The period of data acquisition for each instrumented site is given in table 6.

The micrometeorological data collected throughout the study were stored as 20-minute averages computed from measurements made during 10 or 30-second sampling intervals. The collection process produced large amounts of data, which are not presented in the report but are available upon request from the U.S. Geological Survey (Las Vegas office). Gaps in the record occurred as a result of instrument failure and the inability of specific instruments to make accurate measurements under certain climatic conditions. ET was calculated from energy fluxes measured and computed from the Bowen ratio for each 20-minute interval, except for those intervals having missing or inaccurate data or during which the Bowen ratio solution was unstable. A typical set of micrometeorological data acquired to solve the energy budget is shown in figure 10 for the 5-day period, September 1-5, 1996, at CMEADW (table 6, pl. 1).

Daily ET was computed by summing ET calculated for each 20-minute period. Daily values were computed only for days having 68 or more 20-minute computations. Energy-budget fluxes and daily ET calculated from the Bowen ratio at CMEADW for the 5-day period, September 1-5, 1996, are shown in figure 11.

Daily ET calculated by the Bowen ratio method at CMEADOW for 1996 is shown in figure 12. The minimum calculated daily ET is near zero on day 326 (November 21) and the maximum is nearly 0.25 inch on day 198 (July 16). The mean of the daily ET values is 0.097 inch. Annual ET for 1996 is 35.4 inches and was computed by integrating the daily ET values calculated for the year. Although a plot of daily ET values shows a general pattern defined by higher rates throughout the late spring and summer months, daily variability is evident (fig. 12*A*). 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 annual ET curve for 1996 at the CMEADW site is compared to computed daily ET values in figure 12*A*. Annual ET calculated by integrating the smoothed ET curve is 35.5 inches and compares favorably to annual ET calculated from daily values (35.4 inches). The smoothed ET curve is assumed to better represent daily fluctuations over a typical year and allows for clear graphical comparisons of ET rates computed by different methods, for different sites, and over multiple years. Any small differences between the smoothed and computed daily ET values shown on figure 12 for the first few and last few values are attributed to artifacts of the fitting algorithm.

Smoothed ET curves calculated from daily ET values computed by other methods are compared to the Bowen ratio curve for 1996 at the CMEADW site in figure 12*B*. Annual ET computed by the different methods identified in the figure ranged from 28.9 to

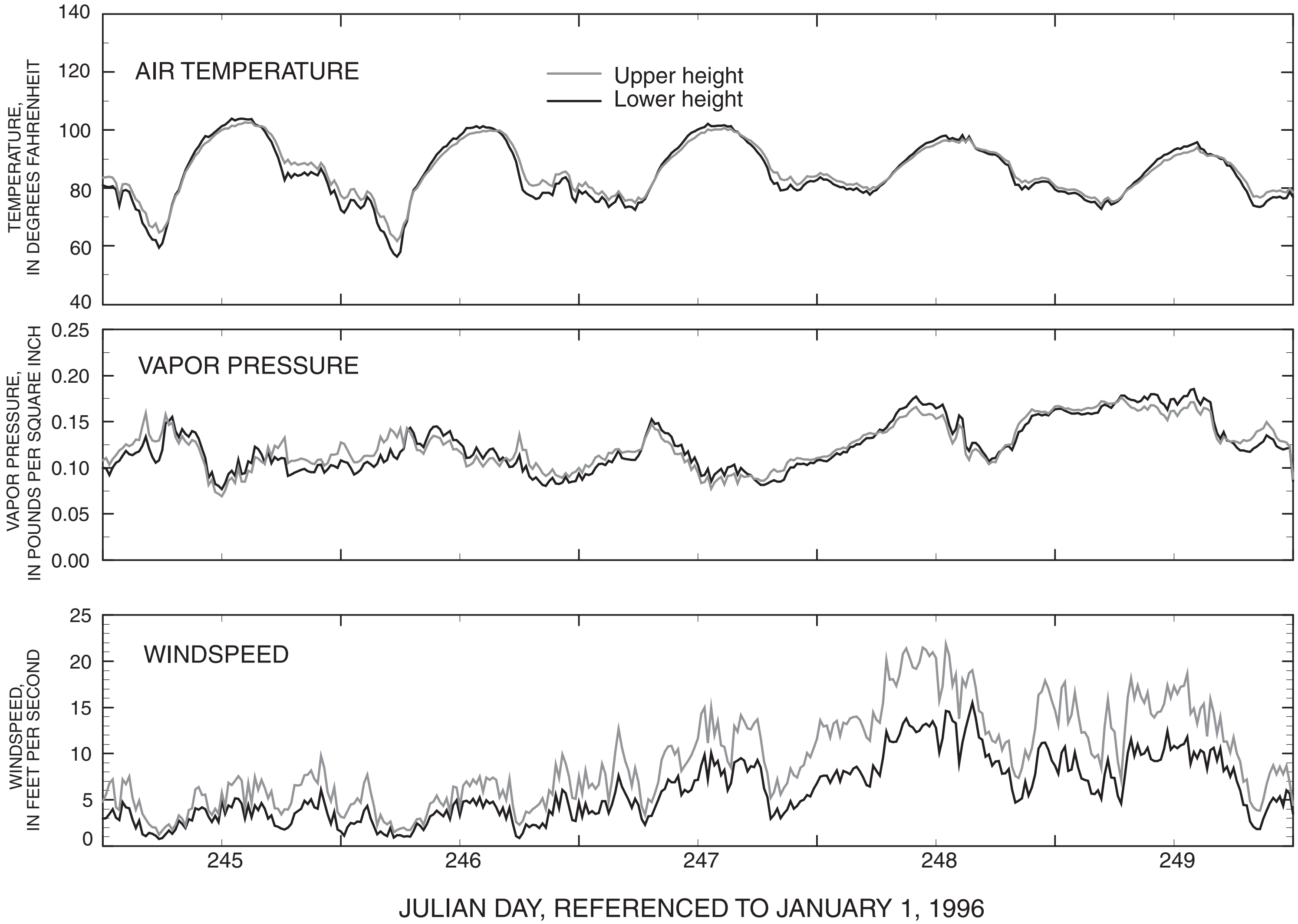


Figure 10. Micrometeorological data collected at Carson Meadows (CMEADW) ET site, September 1-5, 1996. Curves constructed from measurements representing 20-minute averaged values.

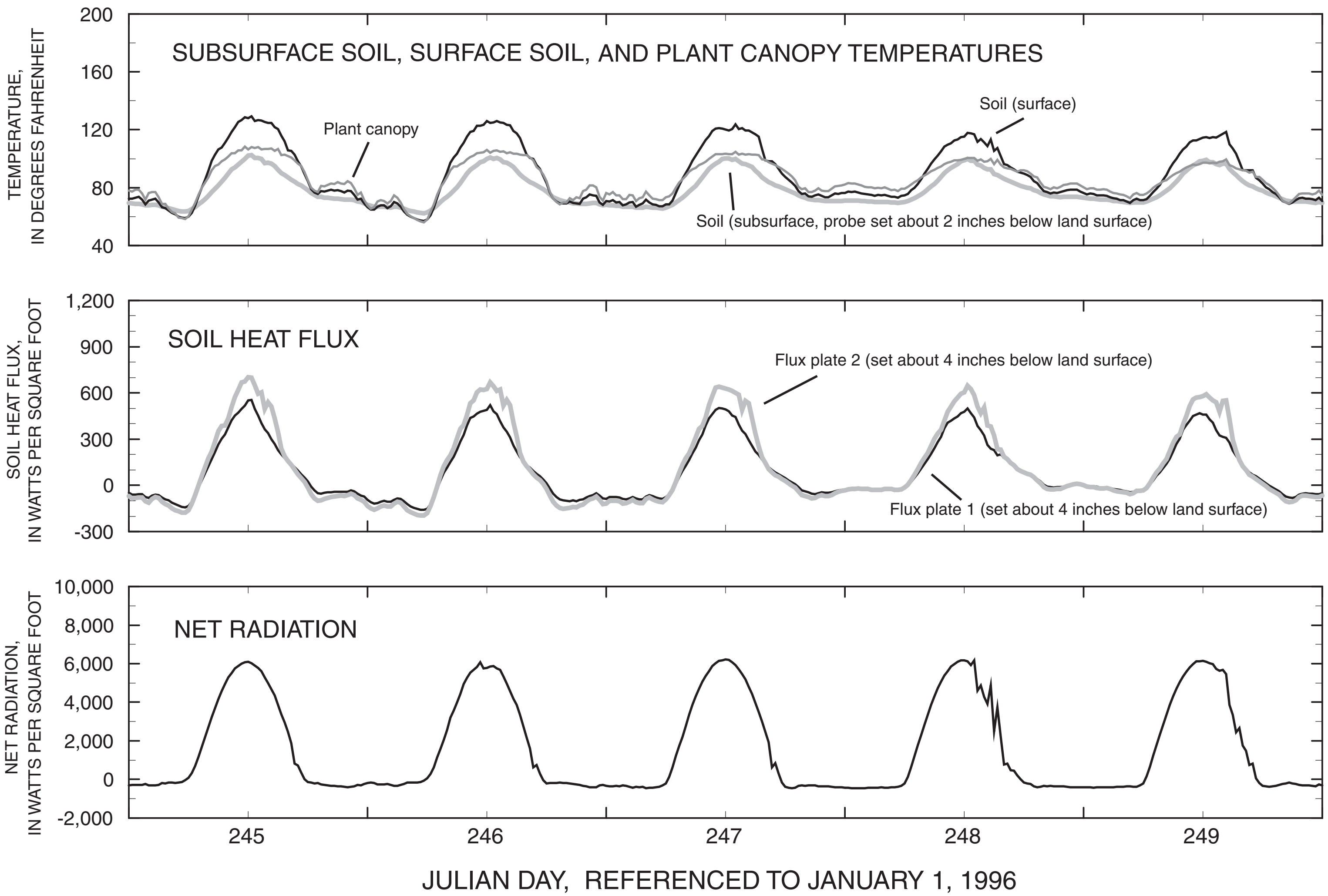


Figure 10. Continued

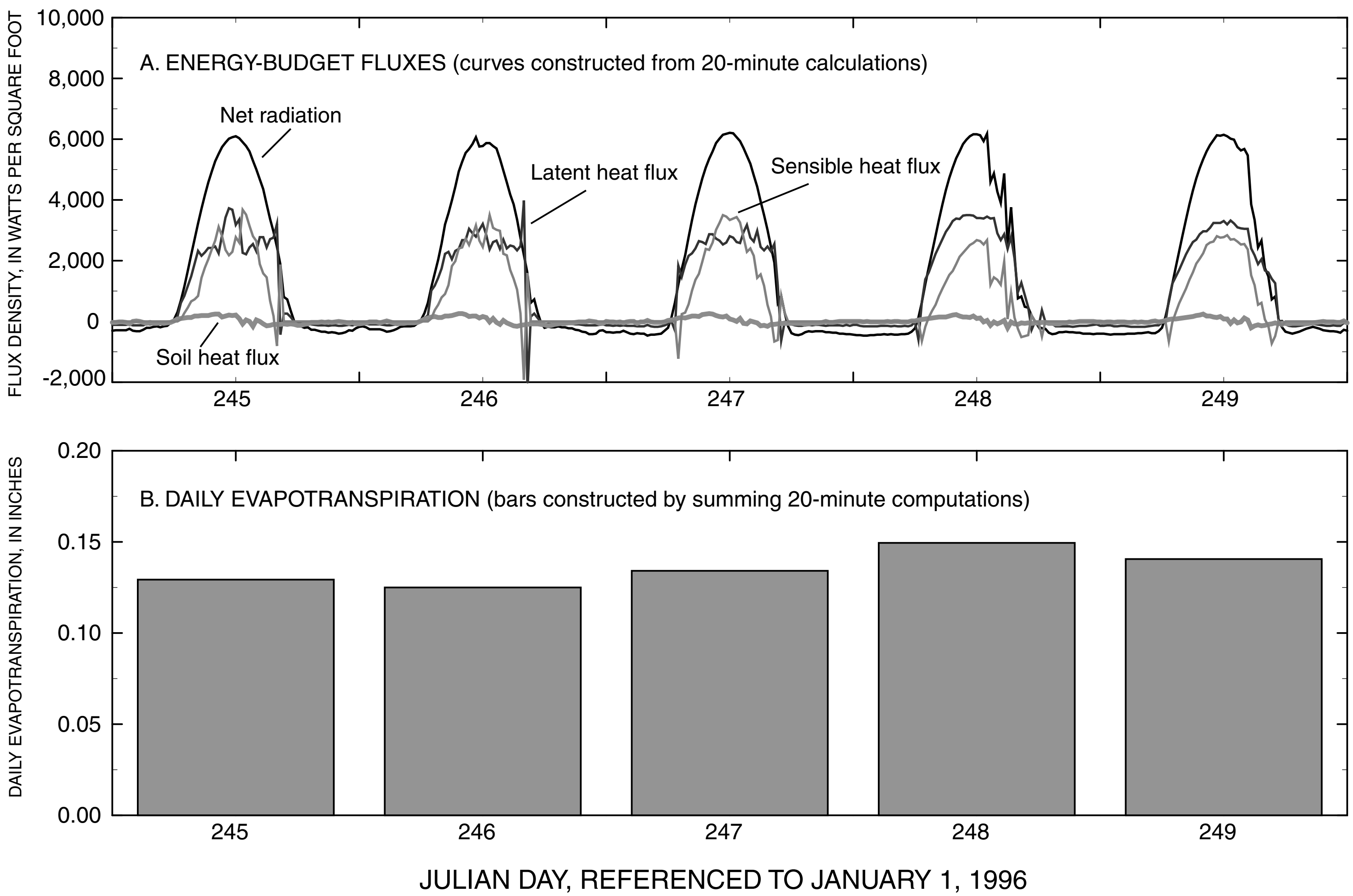


Figure 11. *(A)* Energy-budget fluxes and *(B)* daily evapotranspiration calculated from micrometeorological data collected at Carson Meadows (CMEADW) ET site, September 1-5, 1996.

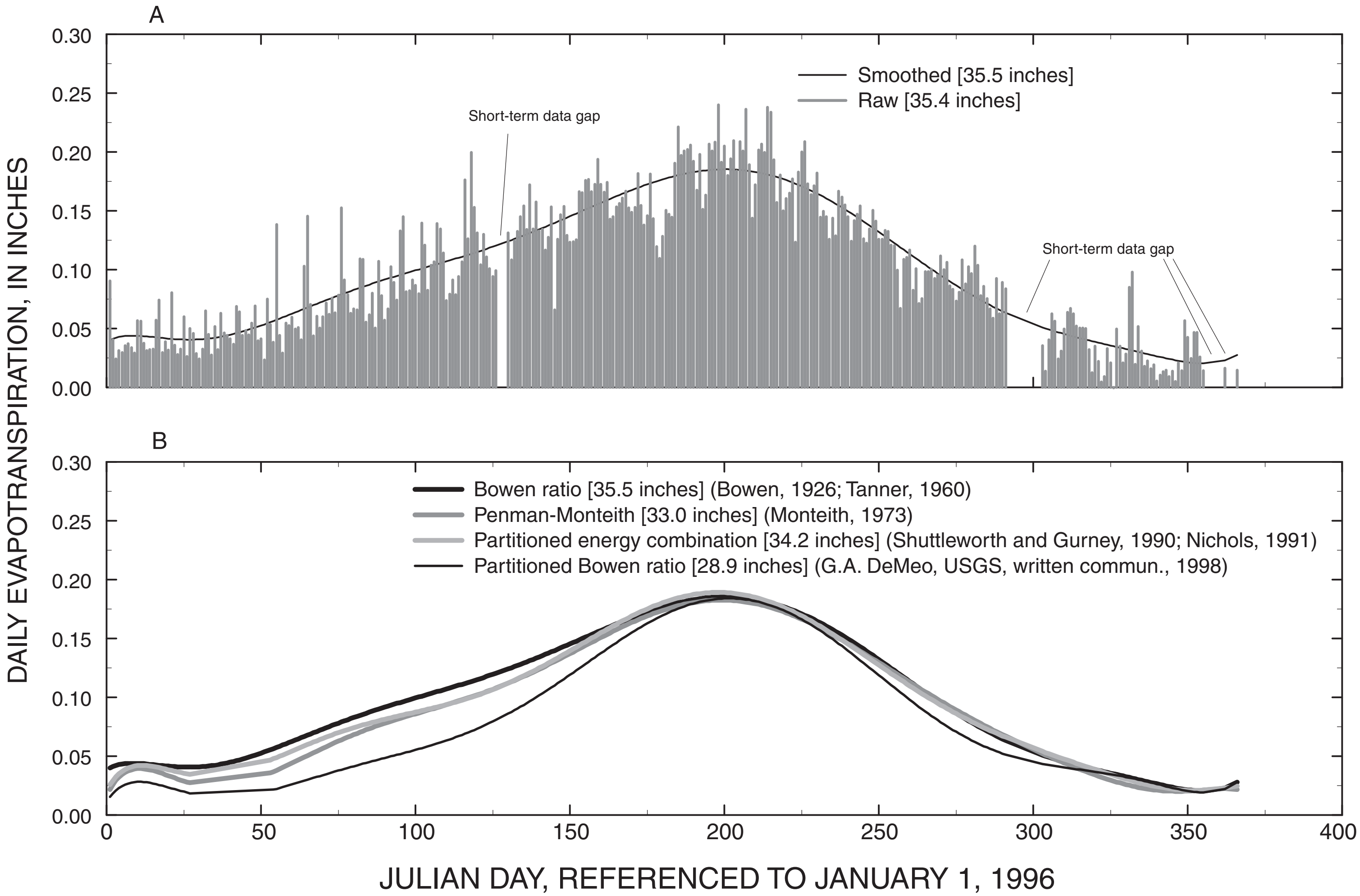


Figure 12. Calculated daily evapotranspiration (ET) at Carson Meadow (CMEADW) ET site for 1996. *(A)* Raw and smoothed annual ET curves calculated by the Bowen-ratio method. *(B)* Annual ET curves calculated by different methods. Number in brackets is annual ET computed for 1996.

35.5 inches. Although the comparison shows some differences, the overall agreement between the methods is considered reasonable. As stated previously, these other methods were used only as independent checks to validate the reasonableness of the Bowen ratio method.

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, which was computed by integrating its ET curve over a 1- or 2-year period, is given in table 7. Estimated average annual rates differed between ET units and ranged from 8.60 ft over open water (Peterson Reservoir, PRESVR) to 0.62 ft over sparse saltgrass (Spring Meadow, SMEADW). A graph combining all ET curves for the period of data collection is shown in figure 13. The figure also shows annual precipitation determined from volumetric rainfall measurements taken during 1995, 1996, and 1997 near Rogers Spring 1 (RGSPR1) site (pl. 1). Annual precipitation for the 3-year period ranged from 2.4 inches in 1996 to 4.8 inches in 1995.

The aggregate graph of ET curves (fig. 13*B*) shows the spatial and temporal differences in ET computed throughout the Ash Meadows area. The individual curves show some significant differences in computed daily and annual ET rates between ET units and also show some differences between multiple sites within an ET unit. Intra-unit differences are greatest in SGV where annual ET ranges from 0.62 ft at Spring Meadow (SMEADW) site to nearly 2 ft at Bole Spring South (BSSOUT) and Rogers Spring 1 (RSPRG1) sites. Although temporally limited, ET rates computed for some sites exhibit daily and annual (year to year) variations. Annual variation is most apparent at Carson Meadows (CMEADW) site (fig. 13*B*) and may be explained in part by differences in precipitation. The ET curve for the CMEADW site indicates higher daily and more annual ET in 1995 than in 1996. The higher rates are consistent with precipitation being greater (by a factor of 2) in 1995 than in 1996, and are likely a response to an increase in water availability. Similarly, the ET curve for the Fairbanks Swamp (FSWAMP) site indicates higher daily rates and more annual ET in 1997 than in 1996.

The ET curve for BSSOUT defines dual ET peaks over each measured calendar year (fig. 13*B*). The first peak can be explained by the presence of standing water that inundates the site during late winter and early spring, and eventually evaporates or drains away. The later peak is likely the typical late spring/early summer peak associated with a period of maximum plant vigor. Although the dual peaks are apparent in the 1996 and 1997 records, the higher initial peak in 1997 is attributed to a greater amount and a prolonged presence of surface water in the early part of 1997.

Table 7. Estimated annual evapotranspiration (ET) at ET sites in Ash Meadows area, Nevada

Site name	Site identifier (pl. 1)	ET-unit identifier [1]	Period of record [2]				Estimated annual ET (feet)
			Processed [3]		Computed [4]		
			Start	End	Start	End	
Bole Spring North	BSNORT	MBS	731	1320	744	1109	2.60
Bole Spring South	BSSOUT	SGV	731	1461	731	1461	1.88
Carson Meadow	CMEADW	DMV	446	1176	446	1176	3.44
Fairbanks Meadow	FMEADW	DGV	1168	1475	1168	1475	[5]3.73
Fairbanks Swamp	FSWAMP	DWV	651	1340	761	1126	3.91
Lower Crystal Flat	LCFLAT	MBS	699	1251	725	1090	2.58
Peterson Reservoir	PRESVR	OWB	869	1336	907	1272	8.60
Rogers Spring 1	RGSPR1	SGV	1	730	1	730	1.92
Rogers Spring 2	RGSPR2	DGV	1	730	1	730	3.23
Spring Meadow	SMEADW	SGV	979	1346	979	1344	0.62

[1] ET units are described in table 3.

[2] Period of record is defined by starting and ending day. Days are referenced to January 1, 1994.

[3] Period of record processed to calculate daily ET shown in figure 13 and on plate 1.

[4] Period of record used to estimate annual ET.

[5] Annual ET rate estimated from less than 1 year of data.

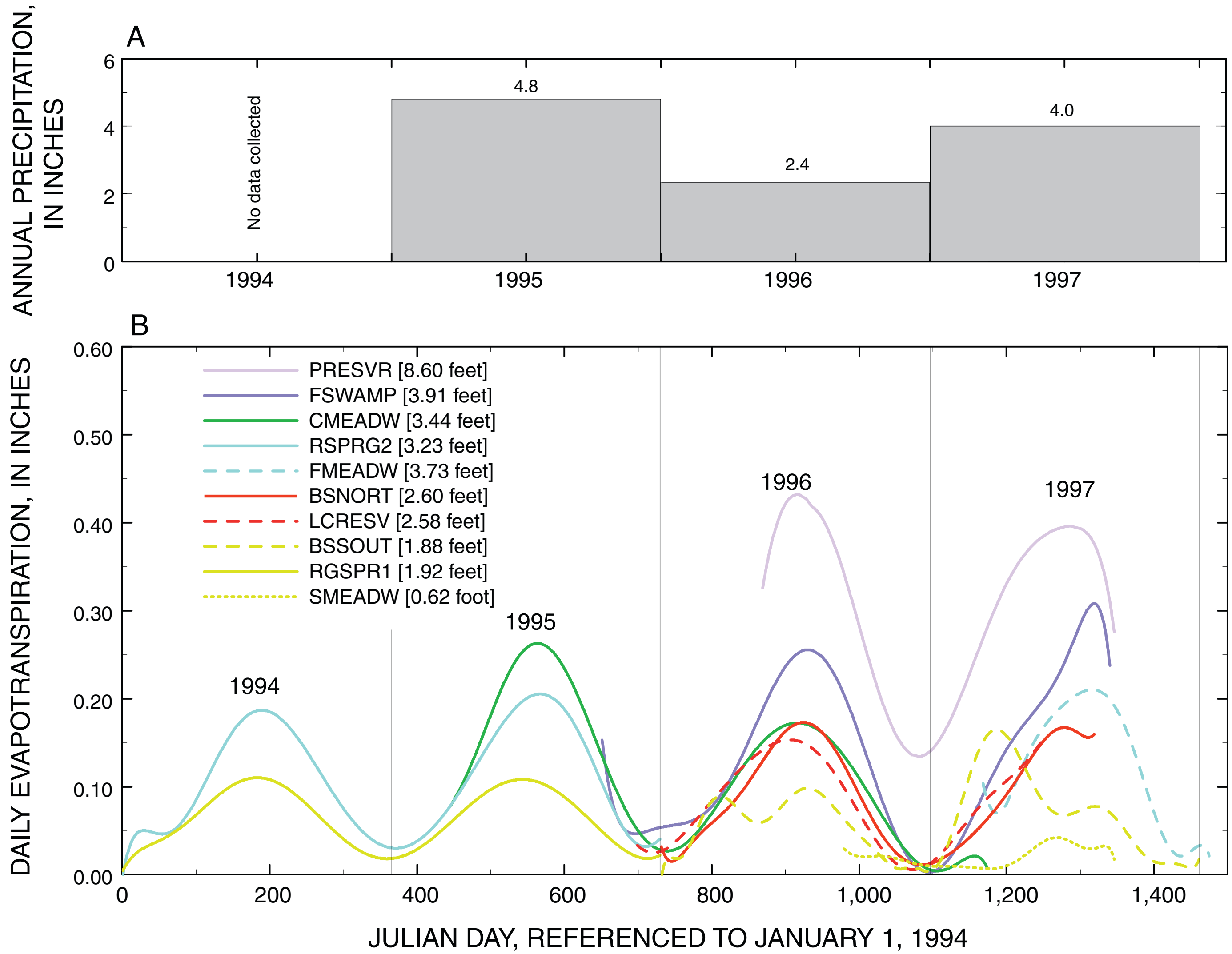


Figure 13. *(A)* Measured annual precipitation and *(B)* calculated daily evapotranspiration (ET) in Ash Meadows area, Nevada. Number above bar is annual precipitation total. Bracketed number is annual ET estimate at each ET site.

One rather anomalous result is the large ratio (in excess of 2) between the open-water evaporation (8.60 ft/yr, fig. 13*B*) and wetland evapotranspiration (3.91 ft/yr, fig. 13*B*). Typically this ratio is assumed to be about one (Hammer, 1989, p. 27). This assumption is based on results of several studies (Christiansen and Low, 1970; Kadlec, 1986; Kadlec and others, 1988), all of which were done in more humid and cooler climates. The annual ET determined for dense wetland vegetation is near that measured in these other studies, thus the high ratio is attributed to the higher open-water rate. A higher open-water rate would be expected considering the other regions' climatic conditions. Another factor contributing to the higher ratio is that the dense mat of dead vegetation (1 to 3 ft thick) and the marsh plant structure (tall and broad-leafed) work together to reduce evaporative losses. The reduction is caused by shading of the water surface and by limited air movement through the vegetative cover (Hammer, 1992, p. 28). Shading effects can drastically reduce winter evaporation as is shown by comparing the winter parts of the PRESVR and FSWAMP daily ET curves in figure 13*B*. Stagnant air creates conditions where the relative humidity is near saturation throughout the thick vegetative covering, minimizing any exchange with drier air. Together these factors are likely accountable for the atypical ratio between open-water and wetland evapotranspiration.

Water-Table Fluctuations

Like other desert areas, Ash Meadows receives little precipitation (fig. 13*A*). Much of the vegetation that thrives throughout Ash Meadows requires more water than is provided by local rainfall and must rely on local ground water for survival. The removal of ground water from the shallow valley-fill aquifer by local phreatophytes and through the evaporative process often is reflected by concurrent changes (fluctuations) in the water table. A network of wells from which to measure and document daily, seasonal, and annual fluctuations in the water table was established to gain greater insight into the ET process at Ash Meadows.

Data Collection Network and Methods

Water-table fluctuations were determined by making depth-to-water measurements in wells located throughout the Ash Meadows area during calendar years 1994 through 1997. Measurements were made on a periodic and, in selected wells, on a continual basis. Wells making up the network were distributed such that most vegetation types, soil moisture conditions, and general depth ranges were represented by at least one well. Well construction and location information is given in tables 12 and 13 in the "Supplemental Data" section at the end of the report.

Twenty-two shallow wells were installed at selected locations because few existed prior to the study. Coincident with the start of the study was an effort by the U.S. Fish and Wildlife Service to eradicate saltcedar within the refuge boundaries. As part of this effort, 12 shallow wells were installed in the area along the northern reach of Carson Slough (fig. 3)—an area overgrown by thick stands of saltcedar. The purpose of these wells was to measure and document any changes in the shallow water table that may result from the eradication effort. Measurements were made by personnel from the U.S. Fish and Wildlife Service and were provided to the U.S. Geological Survey during the period of study. Shallow wells installed during the study range in depth from 5.8 to 20 ft. Shallow-well locations are shown on plate 2.

Although the major focus of monitoring water levels was on the shallow water table, 28 wells having depths equal to or greater than 90 ft were measured periodically throughout the Ash Meadows area (table 13). These wells were constructed prior to the study and are referred to as existing wells. Depth-to-water measurements in these deeper wells provided information on water-level fluctuations in areas where the depth of the water table exceeded 25 ft and in deeper parts (more than 50 ft below the water table) of the ground-water flow system. Five existing wells having depths of less than 60 ft also were measured periodically. Depth measurements from these wells were used to document annual fluctuations in the water level in areas where the water table was relatively shallow (less than 25 ft) and where ground-water ET was considered insignificant (described as "UCL" or unclassified area in table 3). For brevity, shallow wells within unclassified areas are referred to as "unclassified shallow wells" throughout the remainder of the report.

Periodic measurements were made monthly in shallow wells from the date of installation through September 1997. On occasion, a monthly measurement could not be obtained due to difficulties in accessing the site. Periodic measurements also were made in other wells existing throughout the area prior to the study, but on a much less frequent basis. The frequency of measurements in these wells varied, but was sufficient to document annual fluctuations.

Continual measurements provided data from which to evaluate the response of the water table to daily changes in hydrologic stress, such as responses resulting from ET. Continual (hourly) measurements were made using down-hole pressure sensors. Sensors were installed in 10 shallow and 2 deep wells. Sensor installations were included at every ET site except at Fairbanks Meadow (FMEADW) and Peterson Reservoir (PRESVR). The data-collection period at each site differed in accordance with the well installation and the period of interest. A barometer installed at Devils Hole well was used to document local air (barometric) pressure changes.

The ET unit in which each well is located is given in tables 12 and 13. The distribution of shallow wells is such that at least one well is within each ET unit (table 3) with two exceptions. The exceptions are ET units OWB (open water body) and SAV (submerged aquatic vegetation). Although no well is in OWB, a staff gage installed as part of the open-water ET site at Peterson Reservoir (fig. 3, pl. 1) was read periodically to measure changes in the reservoir water-surface elevation. Only one shallow well, augered to depth of 8.25 ft, is in ET unit DWV (dense wetland vegetation). Eight shallow wells having depths ranging from 8.4 to 20 ft are in ET unit DMV (dense meadow vegetation). Seven shallow wells, ranging in depth from 5.8 to 20 ft, are in ET unit DGV (dense grassland vegetation). The largest ET unit, SGVA (sparse grassland vegetation), is represented by 15 wells that range in depth from 6.25 to 17.8 ft. Two wells, with depths of 12.0 and 13.2 ft, are in ET unit MBS (moist bare soil). Only one shallow well, located near Amargosa Flat, a dry playa a few miles northwest of Ash Meadows proper (fig. 3), is within the unclassified area (UCL, table 3).

Twelve deep wells are within classified ET units—seven in SGV (sparse grassland vegetation); four in DGV (dense grassland vegetation); and one in DMV (dense meadow vegetation). All these wells are deeper than 90 ft. Considering their depth, any measured annual and daily water-level fluctuation is likely caused by some hydrologic stress other than local ET.

Annual and Daily Fluctuations

The shallow water table, as determined from depth-to-water measurements made in shallow wells throughout the Ash Meadows area, fluctuates on an annual and daily basis. Fluctuations are primarily a response to local ET and the magnitude and timing of the fluctuation differs with well depth, vegetation and soil conditions, climate, and distance from a surface-water source. Other factors of less significance affecting the shallow water table are changes in air (barometric) pressure and earth tides. Annual and daily fluctuations also were noted in the deeper wells and are attributed primarily to air-pressure and earth-tide responses.

Annual fluctuations in water level measured in each of the shallow wells and in Peterson Reservoir are summarized by ET unit in table 8. The table gives the minimum and maximum depths to water, and the magnitude of the fluctuation measured at each site for each year of data collection. Annual fluctuations are based on hourly or periodic measurements (pls. 1 and 2). Maximum and minimum values determined from periodic measurements may not be indicative of the actual annual high and low in the water level because of the long periods between measurements (monthly or greater). Annual fluctuations, formulated from hourly (pressure-sensor) measurements taken at each instrumented ET site, are shown with calculated daily evapotranspiration on plate 1 and are shown by ET unit in figure 17 in the “Supplemental Data” section.

Depth-to-water measurements made in the shallow wells show a wide range in the annual fluctuation of the water table. Annual fluctuations ranged from 0.4 ft at the Fairbanks Swamp well in ET unit DWV to 10.2 ft at well CS-07 in ET unit DGV (table 8, pl. 2). The annual fluctuation varied not only between ET units, but also within some ET units. The measured within-unit variation ranged from 2.4 to 9.4 ft in DMV, from 2.4 to 10.2 ft in DGV, from 0.7 to 9.2 ft in SGV, and from 1.6 to 6.0 ft in MBS. Variations measured within these units are not unexpected considering that each unit includes areas of different vegetation, and of varying soil and moisture conditions. Variations within ET units OWB, SAV, and DWV could not be evaluated (an insufficient number of wells), but the range is expected to be small considering their fairly homogeneous makeup.

Table 8. Summary of annual fluctuations in water levels measured in shallow water-table wells and at staff gage in Ash Meadows area, Nevada

[Sites grouped by ET unit (table 3). Well depth referenced to land-surface datum. Gage depth at Peterson Reservoir referenced to top of vertical outflow pipe. Negative depth implies water level above datum. Double dash indicates missing or non-applicable entry.]

Site Name: Identifies well or staff gage. All CS wells measured by U.S. Fish and Wildlife Service. Site location given in table 12.

Depth-to-water measurement: Minimum and maximum are first occurrence of measured value during year. (mn) is annual minimum for ET unit over duration of study. (mx) is annual maximum for ET unit over duration of study. Measurements affected by local precipitation, short-term flooding, or long-term rise in water level are given in table but are not used in determining the annual minimum or maximum.

Site name	Well depth (feet)	Year [1]	Depth-to-water measurement					Comments
			Annual minimum		Annual maximum		Annual fluctuation (feet)	
			Feet	Month and day	Feet	Month and day		
Open Water Body (OWB)								
Peterson Reservoir staff gage	--	[2]1996	-0.3	03-04	2.3	09-08	2.6	Water-surface elevation moderated by discharge from outflow pipe and perennial inflow.
		1997	-0.2	03-29	2.3	09-05	2.5	
Dense Wetland Vegetation (DWV)								
Fairbanks Swamp Well	8.25	[2]1995	.3(mn)	05-09	2.4(mx)	09-17	2.1 (mx)	Water level sustained in part by perennial flow in nearby springflow drainage.
		1996	.3 (mx)	03-29	1.6	07-25	1.3	
		1997	.3	03-15	0.7 (mn)	08-21	0.4 (mn)	
Dense Meadow Vegetation (DMV)								
Carson Meadows Well	10.9	1995	[3]-.6	03-14	--	--	--	Decreased annual water-level fluctuation measured in 1997 may be result of brushfire in March 1997 that destroyed much vegetation in general area.
		1996	2.0	02-23	6.5	09-08	4.5	
		1997	[3]-.2	03-05	--	--	--	
			3.3	02-27	8.4	09-27	5.1	
			3.8	02-08	6.7	09-18	2.9	
Cold Spring Well	17.35	1995	[3]-.6	03-14	8.4	10-10	--	
		1996	4.2	04-26	7.9	10-02	3.7	
		1997	3.1	05-09	7.3	09-18	4.2	
CS-03	8.4	1995	1.8	04-24	4.8 (mn)	08-14	3.0	
		1996	1.3 (mn)	03-25	5.7	09-20	4.4	
		1997	1.6	03-19	6.2	08-18	4.6	

Table 8. Summary of annual fluctuations in water levels measured in shallow water-table wells and at staff gage in Ash Meadows area, Nevada—Continued

Site name	Well depth (feet)	Year [1]	Depth-to-water measurement: Annual minimum: Feet	Annual minimum: Month and day	Annual maximum: Feet	Annual maximum: Month and day	Annual fluctuation (feet)	Comments
CS-06	13.2	1995	3.7	05-22	10.3	09-21	6.6	
		1996	2.2	04-18	9.1	09-20	6.9	
		1997	2.7	04-18	9.1	09-21	6.4	
CS-09	20.0	1995	11.0 (mx)	05-22	[4]16.8	01-24	--	Long-term rise in water level noted in record and may be related to eradication of saltcedar by U.S. Fish and Wildlife Service.
		1996	6.3	04-18	14.8	09-21	3.8	
		1997	3.5	04-18	13.7	09-20	7.4	
					12.3	09-21	8.8	
CS-10	20.0	1995	--	--	[4]18.0	01-24	--	
			10.0	05-25	15.5	10-16	5.5	
		1996	10.0	04-18	16.3(mx)	09-20	6.3	
		1997	6.7	04-18	14.2	09-21	7.5	
CS-11	15.5	1995	[3]2.0	03-17	13.7	11-20	--	
		1996	4.6	04-18	14.0	09-20	9.4 (mx)	
		1997	2.5	04-18	11.5	09-21	9.0	
CS-12	11.3	1995	[3]2.6	03-17	8.8	10-16	--	
		1996	6.8	04-18	9.2	09-20	2.4 (mn)	
		1997	5.9	04-18	9.7	08-18	3.8	
Dense Grassland Vegetation (DGV)								
American Resources Well	9.7	1995	[3]0.0	04-17	--	--	--	
			.2	02-02	8.4	10-10	8.2	
		1996	.8	03-27	8.7	10-02	7.9	
		1997	3.2	04-04	7.9	09-18	4.7	
CS-01	10.6	1995	5.5	04-24	9.2	09-21	3.7	
		1996	5.0	03-25	8.8	08-19	3.8	
		1997	5.0	03-19	9.3	08-18	4.3	
CS-05	13.5	1995	7.1	04-24	11.4	09-21	4.3	
		1996	6.9	04-18	11.1	09-20	4.2	
		1997	7.0	03-19	10.7	09-21	3.7	

Table 8. Summary of annual fluctuations in water levels measured in shallow water-table wells and at staff gage in Ash Meadows area, Nevada—Continued

Site name	Well depth (feet)	Year [1]	Depth-to-water measurement					Comments
			Annual minimum		Annual maximum		Annual fluctuation (feet)	
			Feet	Month and day	Feet	Month and day		
CS-07	17.4	1995	9.7	03-17	16.4	10-16	6.7	Long-term rise in water level noted in record and may be related to eradication of saltcedar by U.S. Fish and Wildlife Service.
		1996	5.4	03-25	15.6	09-20	10.2 (mx)	
		1997	4.0	02-18	13.1	08-18	9.1	
CS-08	20.0	1995	11.3 (mx)	03-17	16.8 (mx)	10-16	5.5	Long-term rise in water level noted in record and may be related to eradication of saltcedar by U.S. Fish and Wildlife Service.
		1996	7.8	04-18	16.0	09-20	8.2	
		1997	6.4	03-19	13.3	09-21	6.9	
F-Meadows Well	6.8	[2]1997	.4	04-04	2.8 (mn)	08-04	2.4 (mn)	
Rogers Spring ET2 Well	5.8	1994	.0 (mn)	12-25	4.7	09-02	4.7	
		1995	.0	01-26	4.0	09-08	4.0	
		1996	.2	02-05	4.5	09-12	4.3	
		1997	.3	01-09	3.7	08-04	3.4	
Sparse Grassland Vegetation (SGV)								
Ash Forest Well	8.5	1995	1.1	02-23	5.3	09-21	4.2	Annual fluctuation in water level may be moderated by local recharge from Crystal Reservoir
		1996	1.4	03-27	4.5	09-12	3.1	
		1997	1.6	04-04	5.0	09-18	3.4	
B-Spring South Well	14.1	1996	1.9	03-27	7.3	09-12	5.4	Standing water noted at surface during period from February through March, but water level remained well below land surface.
		1997	1.9	04-04	7.1	09-18	5.2	
Big Spring Well	9.25	1995	1.8	02-13	2.8	09-21	1.0	Annual fluctuation in water level moderated by drainage from Big Spring.
		1996	1.9	03-27	3.0	08-01	1.1	
		1997	1.9	04-04	2.6 (mn)	09-18	0.7 (mn)	

Table 8. Summary of annual fluctuations in water levels measured in shallow water-table wells and at staff gage in Ash Meadows area, Nevada—Continued

Site name	Well depth (feet)	Year [1]	Depth-to-water measurement: Annual minimum: Feet	Annual minimum: Month and day	Annual maximum: Feet	Annual maximum: Month and day	Annual fluctuation (feet)	Comments
Carson Slough 3 Well	13.25	1994	0.5	02-25	7.4	10-04	6.9	Minimum depth-to-water measurement may be affected by recharge from intermittent flow in Carson Slough.
		1995	[3]0.0	02-02	--	--	--	
		1996	0.5	02-23	7.2	10-10	6.7	
		1997	0.5	03-10	7.4	10-02	6.9	
			0.4	03-05	6.1	09-18	5.7	
Carson Slough South Well	12.35	1995	0.1	02-02	6.7	10-10	6.6	Water-level fluctuation moderated by intermittent flow in nearby drainage channel.
		1996	0.1	03-27	6.3	10-02	6.2	
		1997	0.1	04-04	5.8	09-18	5.7	
Carson Slough Terrace Well	12.7	1996	1.1	03-10	7.9	10-02	6.8	Minimum depth-to-water measurement may be affected by recharge from intermittent flow in Carson Slough.
		1997	1.1	03-05	6.7	09-18	5.6	
Carson West Well	17.8	1995	0.1 (mn)	03-04	9.3	11-09	9.2 (mx)	Minimum depth-to-water measurement may be affected by recharge of standing water noted at surface during period February through May.
		1996	0.2	03-31	9.2	10-02	9.0	
		1997	0.1	04-04	7.7	08-04	7.6	
CS-02	11.5	1995	5.1	04-24	8.5	08-14	3.4	
		1996	4.6	03-25	8.9	09-20	4.3	
CS-04	11.0	1995	5.6	04-24	9.8	09-21	4.2	
		1996	5.5	04-18	9.6	09-20	4.1	
		1997	5.4	03-19	9.1	08-18	3.7	
Peterson Reservoir Well	10.7	1995	[3]-0.2	02-02	--	--	--	Water-table fluctuation may be moderated by recharge from Peterson Reservoir.
		1996	0.5	03-30	3.7	09-21	3.2	
		1997	0.7	03-10	4.4	09-12	3.7	
			0.9	04-04	4.1	09-18	3.2	
Rogers Spring ET1 Well	6.25	1994	0.7	02-24	7.4	09-14	6.4	Well went dry in July. Well replaced with Rogers Spring ET1-D well on July 25, 1994.
Rogers Spring ET1-D Well	10.0	1995	[3]-0.2	03-11	--	--	--	
			0.7	01-22	7.0	09-19	6.3	
		1996	0.5	04-01	7.0	09-21	6.5	
		1997	0.6	04-04	5.7	08-04	5.1	

Table 8. Summary of annual fluctuations in water levels measured in shallow water-table wells and at staff gage in Ash Meadows area, Nevada—Continued

Site name	Well depth (feet)	Year [1]	Depth-to-water measurement: Annual minimum: Feet	Annual minimum: Month and day	Annual maximum: Feet	Annual maximum: Month and day	Annual fluctuation (feet)	Comments
Spring Meadows Rd Well	14.2	1995	3.8	04-17	7.6	09-21	3.8	
		1996	3.6	03-28	7.4	10-08	3.8	
		1997	3.9	04-04	6.9	08-22	3.0	
SW Drainage North Well	14.5	1995	5.6	03-30	10.0	09-21	4.4	Decreased annual water-level fluctuation measured in 1997 may be result of brushfire in March 1997 that destroyed much of vegetation in general area.
		1996	6.6	03-10	10.6 (mx)	10-02	4.0	
		1997	6.8 (mx)	04-08	8.9	09-18	2.1	
SW Drainage South Well	9.75	1995	3.8	04-24	8.1	07-05	4.3	Water levels affected by controlled flow in local drainage channel and occasional surface flooding.
		1996	3.4	12-03	8.1	07-02	3.7	
		1997	2.0	02-05	7.3	09-18	5.3	
Moist Bare Soil (MBS)								
B-Spring North Well	13.2	1996	0.0	04-21	6.0 (mx)	10-20	6.0 (mx)	
		1997	-0.1	04-16	4.2	09-18	4.3	
Lower Crystal Well	12.0	1995	-0.1 (mn)	01-09	1.8	09-05	1.9	Water-table fluctuation may be moderated by recharge from nearby reservoirs.
		1996	0.2 (mx)	02-27	2.5	09-27	2.3	
		1997	0.1	01-05	1.7 (mn)	08-21	1.6 (mn)	
Unclassified (UCL)								
Amargosa Flat Playa Well	14.5	1995	3.9	03-14	5.6	09-20	1.7	
		1996	4.2	03-27	5.7	09-19	1.5	
		1997	4.1	04-04	5.1	09-18	1.0	

[1] Calendar year 1997 measurements ended September 1997.

[2] Annual statistics based on a partial year of record but assumed to cover annual fluctuation.

[3] Minimum depth-to-water measurement affected by local precipitation or flooding.

[4] Water level rose during calendar year.

The largest measured water-table fluctuations are within ET units in “dryer” areas at locations most distant from a surface-water source (table 8). Annual fluctuations of nearly 10 ft were measured within ET units DMV and SGV. The smallest measured annual fluctuations are in ET units dominated by standing water (OWB and DWV) or at sites near a surface-water source providing a continuous supply of water throughout the year, even during periods of high ET (pl. 1).

Depth-to-water measurements also showed a wide range in their annual minimum and maximum depths. The annual minimum depth to water occurred in winter or early spring (table 8, fig. 17, pls. 1 and 2), whereas, the annual maximum occurred in late summer or fall. The annual minimum depth ranged from near land surface for wells in “wet” areas to 11.3 ft at well CS-08 in ET unit DGV (table 8). The annual maximum depth ranged from 0.7 ft at Fairbanks Swamp well in ET unit DWV to 16.8 ft at well CS-08. As was true of the annual water-table fluctuation, the annual minimum and maximum depth to water also varied among wells within the same ET unit. Generally, the greatest variation occurred in “dryer” and more densely vegetated ET units (DMV and DGV). The annual minimum and maximum depths measured within DMV ranged from 1.3 to 11.0 ft and from 4.8 to 16.3 ft, respectively, and within DGV ranged from near 0 to 11.3 ft and from 2.8 to 16.8 ft (table 8). The smallest minimum depths to water (shallowest water table) were measured in wells near perennial surface-water sources or in areas flooded during the cooler periods of the year. The largest maximum depths to water (deepest water table) were measured in the CS wells, all of which are in or near dense stands of saltcedar.

Annual fluctuations in the depth to water at a given ET site generally lag daily ET such that the annual maximum occurs shortly after daily ET reaches a maximum and the annual minimum shortly after ET reaches a minimum (pl. 1). This delay indicates that the fluctuation in the water table is largely a response to a change in ET rate. Somewhat contrary to this conclusion is the observation that the larger changes in water level occur at sites of low to moderate ET, and the smaller changes at sites of higher ET (pl. 1). This quandary is explained by the presence of a surface-water source near sites of higher ET. The nearby water source provides sufficient water to replace much of the water lost through local ET, thus helping maintain the level of the water table, and as well, the local vegetation.

Although a decline in the water table is a good indicator of ongoing local ET within an area (pl. 1), the magnitude of the annual decline is not necessarily indicative of the rate of ET. The annual decline of the water table depends on many factors—including the depth to the water table and the distance to a local surface-water source. Aquifer and soil properties, and soil-moisture conditions definitely influence the magnitude and timing of the response of the water table to local changes in ET.

Annual changes in water levels measured in 10 of the deep wells and 3 of the unclassified shallow wells existing prior to the study are summarized in table 9. The general differences between measured annual water-level fluctuations in deep and shallow wells are evident by comparing tables 8 and 9 and are illustrated in figures 18-22 in the “Supplemental Data” section. The annual fluctuations measured in deep wells generally are smaller and more subdued than those measured in shallow wells. The greatest differences occur between deep wells and shallow wells within an ET unit and distant from a surface-water source. For brevity, the remainder of the report refers to these shallow wells as “distant shallow wells.” Annual fluctuations measured in wells where the water table is at a depth of more than 60 ft or where the well is open to a zone below the water table were less than 2 ft (table 9); whereas, those measured in distant shallow wells ranged from about 3 ft to more than 10 ft (table 8). The larger annual fluctuations noted in distant shallow wells (figs. 18-22) imply that the net loss of ground water by ET is greater in those areas where the water table is relatively shallow.

A comparison of the water levels measured in the distant and unclassified shallow wells (tables 8 and 9) shows less fluctuation at unclassified locations. The largest fluctuation at any unclassified location was 2.4 ft and was measured in the Mine Shaft well (table 9). This atypically large fluctuation is not likely a response to evapotranspiration from the shallow valley-fill aquifer, but instead to evaporation directly from the water surface exposed to the atmosphere through the large-diameter shaft opening. The smaller annual fluctuations measured in the unclassified area imply less local ET, and thus support the delineation as an area of minimal ET by the classification procedure.

The water table shows only a minimal response to measured changes in annual precipitation. Rainfall data collected from 1995 through 1997 indicate that only 2.4 inches of precipitation fell in 1996 as compared

Table 9. Summary of annual fluctuations in water levels measured in selected existing wells, Ash Meadows area, Nevada

[Wells grouped into deep and unclassified categories. Well locations given in table 12. Depths referenced to land-surface datum. Negative depth implies water level above land surface.]

Well name	Well depth (feet)	Year [1]	Depth-to-water measurement: Annual minimum, Feet	Annual minimum, Month and day	Annual maximum, Feet	Annual maximum, Month and day	Annual fluctuation (feet)	Comments
Deep Wells								
Devils Hole Well	200	1994	47.9	02-08	48.3	01-12	0.4	
		1995	47.9	05-12	48.2	12-25	0.3	
		1996	48.0	03-23	48.4	10-22	0.4	
		1997	47.9	04-04	48.3	01-06	0.4	
Mercury Farms Well	120	1994	7.6	07-01	8.2	09-12	0.6	Moderate annual water-level fluctuation
		1995	6.2	05-30	7.5	09-21	1.3	
		1996	6.1	04-26	8.0	11-08	1.9	
Peterson Well	450	1994	4.4	02-14	5.4	09-13	1.0	Moderate annual water-level fluctuation
		1995	4.2	02-22	5.4	09-21	1.2	
		1996	4.5	03-10	5.4	09-12	0.9	
Point of Rocks South Well	586	1994	8.9	12-24	9.8	01-01	0.9	Long-term water–level recovery.
		1995	8.8	05-11	9.5	07-08	0.7	
		1996	8.5	12-31	9.2	01-06	0.7	
		1997	7.8	10-23	8.5	01-01	0.7	
Rogers Spring Well	202	1994	2.7	03-22	4.4	08-30	1.7	Moderate annual water-level fluctuation.
		1995	2.4	01-31	4.1	09-20	1.7	
		1996	2.7	02-28	4.2	08-28	1.5	
		1997	2.8	01-21	3.8	08-20	1.0	
Spring Meadows 2	415	1994	12.6	02-14	13.4	09-12	0.8	
		1995	12.6	02-22	13.6	09-21	1.0	
		1996	13.1	03-12	13.6	09-19	0.5	

Table 9. Summary of annual fluctuations in water levels measured in selected existing wells, Ash Meadows area, Nevada—Continued

Well name	Well depth (feet)	Year [1]	Depth-to-water measurement					Comments
			Annual minimum		Annual maximum		Annual fluctuation (feet)	
			Feet	Month and day	Feet	Month and day		
Spring Meadows 9	280	1994	18.9	04-06	20.4	09-13	1.5	Moderate annual water-level fluctuation.
		1995	18.7	04-18	20.4	10-10	1.7	
		1996	19.1	04-26	20.5	10-02	1.4	
		1997	19.3	04-04	20.5	09-18	1.2	
Spring Meadows 12	265	1994	74.2	04-06	74.4	12-14	0.2	
		1995	74.3	02-22	74.4	09-21	0.1	
		1996	74.3	03-12	74.5	12-04	0.2	
Spring Meadows 17	500	1994	8.2	12-14	8.6	07-01	0.4	
		1995	8.2	09-21	8.5	07-05	0.3	
		1996	8.1	09-19	8.3	03-12	0.2	
Trenary Well	100	1994	13.2	12-14	13.6	09-12	0.4	Long-term water-level recovery.
		1995	12.8	05-09	13.3	09-21	0.5	
		1996	12.6	12-03	12.8	03-12	0.2	
Unclassified Shallow Wells								
Buck Mining Hand Dug Well	19.4	1994	16.6	04-06	17.2	06-30	0.6	
		1995	16.5	02-22	17.3	09-20	0.8	
		1996	16.6	03-12	17.2	09-19	0.6	
IMV Borehole	15	1994	6.0	07-01	6.6	09-13	0.6	Moderate annual water-level fluctuation.
		1995	5.2	05-10	6.8	11-08	1.6	
		1996	5.6	06-18	6.8	01-09	1.2	
		1997	4.8	05-09	6.3	01-09	1.5	
Mine Shaft	57	1994	18.3	04-07	20.1	09-13	1.8	Large annual water-level fluctuation. Fluctuation may be result of local evaporation directly from water surface exposed to atmosphere.
		1995	17.9	04-18	20.3	09-21	2.4	
		1996	18.6	04-26	20.3	09-12	1.7	

[1] Calendar year 1997 measurements ended September 1997.

with 4.8 inches in 1995 and 4.0 inches in 1997 (fig. 13). Only two wells (Carson Meadows and Lower Crystal; pls. 1 and 2) show any significant correlation between annual changes in the water table and precipitation. The response in these wells to precipitation changes was a greater (deeper) maximum depth to water and larger annual fluctuation during the year of lesser precipitation. Although fluctuations measured in other shallow wells show little correlation to the measured changes in precipitation, any response may have been masked by other factors potentially affecting the water level, such as the saltcedar eradication or natural drainage restoration efforts by the U.S. Fish and Wildlife Service.

In general, water-level altitude increases with well depth (figs. 23-25 in "Supplemental Data" section). This increase in altitude indicates upward flow. Upward flow is consistent with the concept of flow from the underlying regional carbonate-rock aquifer moving diffusely upward into the overlying shallow valley-fill aquifer and supports the possibility of diffuse upflow being a source of some water lost through ET.

The water table as measured in shallow wells throughout the area also fluctuates on a daily basis. The shape, magnitude, and phase of the daily fluctuation varied between wells and over time, and are typified in figures 14 and 15 and also in figures 23-25. Reasons for observed differences in daily fluctuations are many and complex, but most likely are caused by differences in ET rate, depth to water, distance from a surface-water source, confinement of the aquifer system, or some combination thereof. The purpose of this report is not to explain or rationalize every difference but rather to evaluate daily fluctuations to help validate concepts of where and how much ET occurs in Ash Meadows.

Daily fluctuations measured in selected shallow wells are shown in figures 23 and 24 for a 30-day period and in figure 25 for a 60-day period. Plots comparing typical daily water-table fluctuations to daily changes in calculated ET over a 10-day period are shown in figures 14 and 15. Change in the daily fluctuation of water table in response to changes in daily ET over a year or more can be seen in plots shown on plate 1. Water levels measured in deeper wells also fluctuated on a daily basis, and their fluctuations are shown with shallow water-table changes in figures 23-25. Hourly air pressures measured at Devils Hole well for the same period are shown in figure 25.

Taken together, figures 14-15 and 23-25 and the plots on plate 1 provide some interesting insights into the evaporation process. In general, the magnitude of the daily fluctuation measured at ET sites decreases with depth and the larger fluctuations occur during periods of high ET when the water table is near the surface. The largest daily fluctuation, nearly 0.30 ft, was measured in the Fairbanks Swamp well at the FSWAMP ET site (fig. 23) during periods of maximum daily ET (pl. 1). Small daily fluctuations (less than 0.05 ft) were measured at nearly every site and were most conspicuous during periods of low ET when the water table was at its deepest annual level. Typical changes measured in the daily response show that the magnitude of the daily fluctuation generally decreased as the water table began declining in response to continuing or increasing ET, and that at greater depths, the phase in the daily fluctuation was shifted from that of the ET.

The daily fluctuation in the water table and ET measured at the Fairbanks Swamp (FSWAMP) and Carson Meadow (CMEADW) ET sites for a 10-day period in early spring are shown in figures 14 and 15, respectively. The long-term trend in the water level at the FMEADW ET site (fig. 14) is flat and the daily fluctuation is opposite and nearly in phase with that of the calculated ET. Whereas, at the CMEADW ET site (fig. 15), the observed long-term trend is downward, the magnitude of the daily fluctuation is much smaller, and the phase is shifted from that of ET. Differences in the magnitude and phase of the water-table curves are likely related, in part, to differences in the depth of the water table. At shallow depths, evaporation removes water directly from the surface of the water table, and transpiration from the zone directly below the water table penetrated by the root systems of the local vegetation. During deeper water-table periods, some water is lost from the partly saturated soil profile above the water table. The water removed from the partly saturated zone is replaced by water rising from the water table by capillary action (Gardner, 1958). The rate of capillary rise controls the movement of water from the water table into the soil profile and depends on many factors including atmospheric conditions, and soil properties and moisture conditions. Capillary rise is not the subject of this report, but does provide a likely explanation for the noted shift and attenuation of the daily fluctuation.

Daily fluctuations also were measured in the two "deeper" wells instrumented with pressure sensors (Devils Hole and Point of Rocks South wells, table 9).

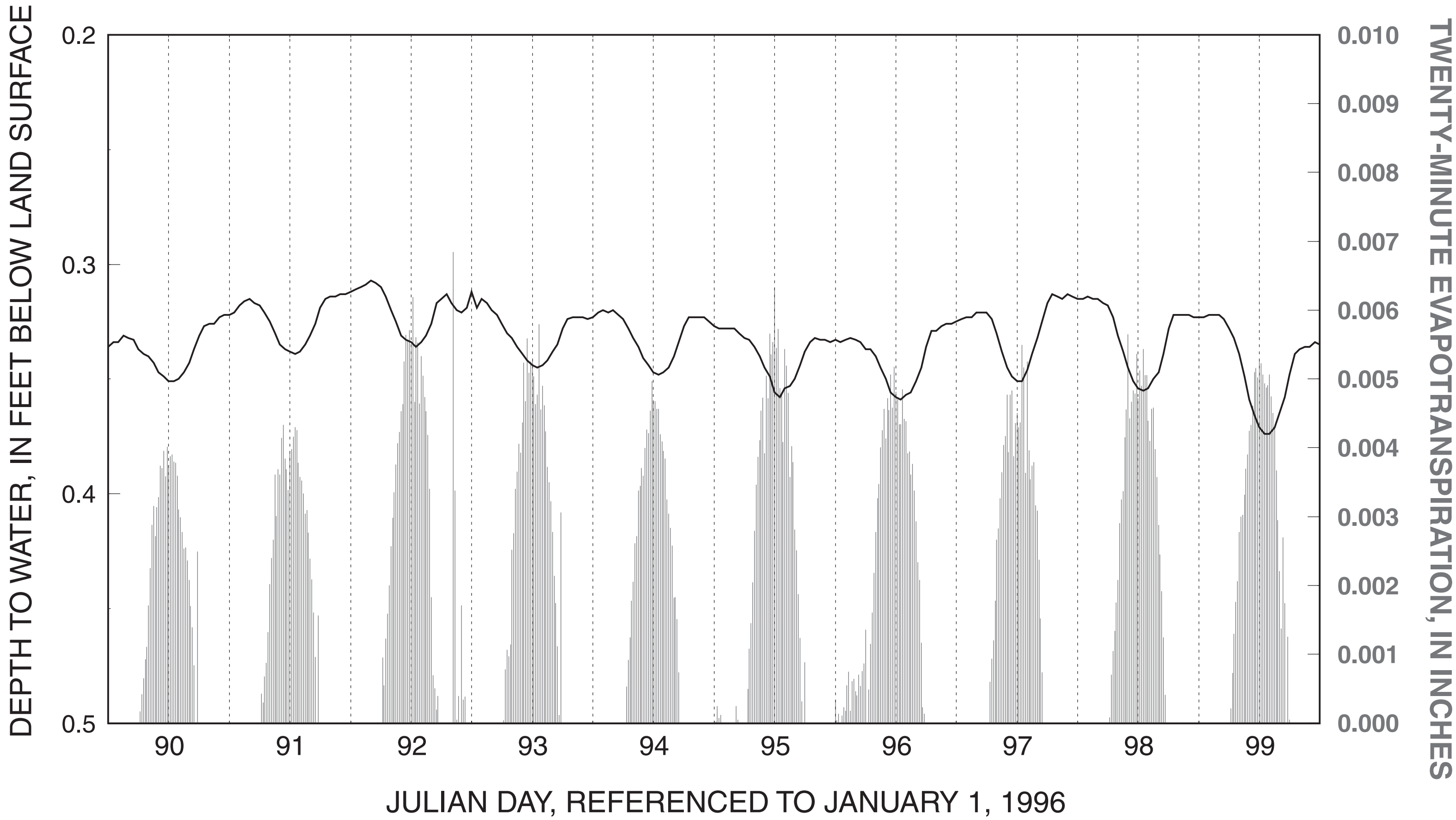


Figure 14. Daily changes in measured water level and calculated evapotranspiration (ET) at Fairbanks Swamp (FSWAMP) ET site, March 30 to April 8, 1996.

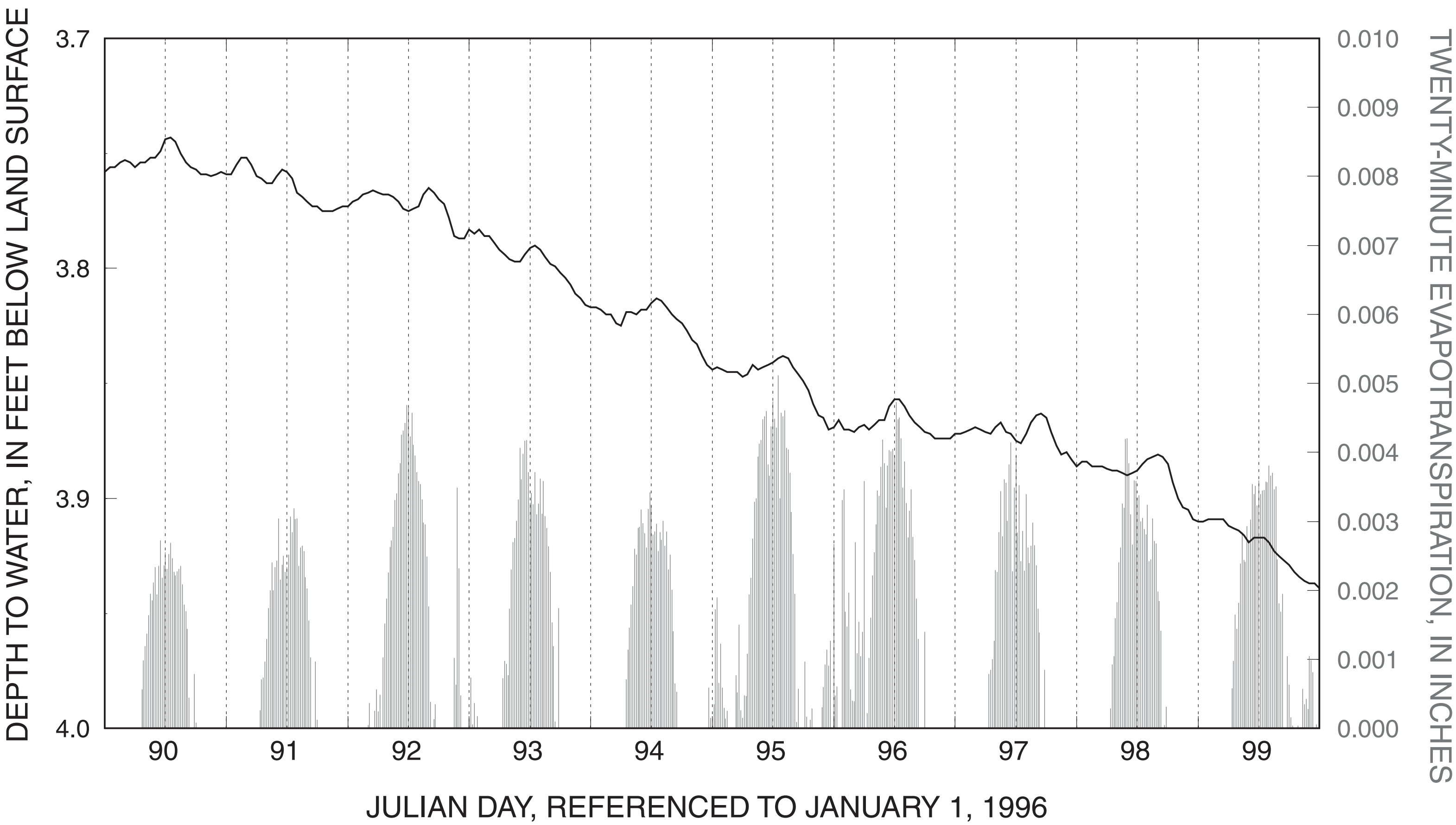


Figure 15. Daily changes in measured water level and in calculated evapotranspiration (ET) at Carson Meadow (CMEADW) ET site, March 30 to April 8, 1996.

Shallow and deep well measurements for two different 30-day periods are shown in figures 23 and 24, and daily measurements for a 60-day period are shown in figure 25. The daily fluctuations measured within the two well groups differ substantially in their magnitude, character, and phase. The water-level fluctuations in the deeper wells are consistent with changes in air pressure (fig. 25) and with daily and higher frequency changes in areal strain induced by earth tides (Galloway, 1993; Galloway and others, 1994). Daily fluctuations, such as those noted in figures 23-25, are documented in other wells throughout the region tapping confined, partly confined, or thick water-table aquifers (Galloway and Rojstaczer, 1988). Fluctuations of this type are unlikely responses to daily ET, but rather are responses to water-level disturbances caused by changes in the aquifer system due to atmospheric loading and earth tides.

Short-term responses to precipitation also are evident in the water-table record of many shallow wells measured throughout the area (figs. 18 and 25). Short-term water table rises are coincident with precipitation but vary among wells in magnitude and duration. The magnitude and attenuation of the rise does not necessarily correlate to depth of the water table. Differences most certainly are related to the amount of precipitation falling at a site, but also are likely related to many other factors including differences in the local vegetation, soil properties, and moisture conditions.

Daily fluctuations in the water table can be a good indicator of ongoing ET, but as is true with the annual fluctuation, the magnitude is not necessarily a reliable gauge of the ET rate. Many factors other than ET rate influence the daily fluctuation in the water table. The fluctuation is governed by the rate of water flowing into and out of the shallow valley-fill aquifer. Factors having a noted effect include the depth of the water table, the existence of a nearby water source, and differences in aquifer and soil properties and local soil-moisture conditions. Although methods attempting to quantify ET on the basis of daily and annual water-level fluctuations were considered, none were attempted due to uncertainties in some of the controlling factors and to the complexity involved in the integration of these factors. Any attempt to calculate ET on the basis of water-level decline would require a better understanding of all the inflow and outflow components contributing to the local water budget and additional knowledge of the hydrologic and physical properties of the soil and aquifer system that govern the movement and storage of water at the site.

Estimates of Annual Evapotranspiration and Ground-Water Discharge

An estimate of ground water annually discharging at Ash Meadows from the regional ground-water flow system, or more specifically from the regional carbonate aquifer, is computed directly from an estimate of the mean annual ET. This approach, as applied in this study, assumes that all ground water discharged from the regional ground-water flow system is evaporated or transpired locally from within the seven ET units identified as areas of substantial ground-water ET (pl. 1). Although springflow is not directly accounted for in the approach, it is considered part of the ET component on the assumption that it is evaporated or recycled back into the shallow ground-water flow system where, eventually, it is evaporated or transpired. As estimated, annual ET includes any precipitation falling on the local area that is evaporated, or that recharges the shallow ground-water flow system and later is evaporated or transpired. The estimate also may include some component of upward leakage (diffuse upflow) from the regional carbonate-rock aquifer. Annual ET is adjusted to remove any water contributed by local precipitation prior to computing ground-water discharge.

Estimates of mean annual ET (in feet and acre-feet) are given in table 10 for each ET unit. Estimates are based on rates calculated from micrometeorological data measured at 10 ET sites (table 7, fig. 13, and pl. 1). A unit having only a single ET site within its boundary is assumed to have an ET rate equal to that of the lone site. The ET rate for a unit having two sites within its boundary is assumed to be the average of the two sites. The rate for the one unit having three sites within its boundary, SGV, is assumed to be a weighted average of the three sites, where the weighting factor was the percentage of area within the unit best reflecting the character of the vegetation and soil conditions observed at the site. Percentages were determined using vegetation indices (Qi and others, 1994) computed from the June TM imagery. Because SAV is dominated by open water, its mean annual rate is assumed to be equivalent to that of open water (OWB). An estimate of the mean annual volumetric ET (in acre-feet) for each ET unit is computed as the product of a unit's total acreage and mean annual ET (in feet). Estimates range from

690 acre-ft for SAV to 9,300 acre-ft for SGV. The mean annual volumetric ET from Ash Meadows is estimated at 21,000 acre-ft (table 10) and was computed by summing the individual ET-unit estimates.

Table 10. Acreage and mean annual evapotranspiration (ET) estimates for ET units and totals for Ash Meadows area, Nevada

ET-unit identifier [1]	Acreage [2]	Mean annual ET	
		Feet [3]	Acre-feet [4]
OWB	158	8.6	1,400
SAV	81	8.6	700
DWV	385	3.9	1,500
DMV	489	3.4	1,700
DGV	1,499	3.5	5,200
SGV	7,160	1.3	9,300
MBS	580	2.6	1,500
Total	10,352		21,000

[1] ET units described in table 3.

[2] Delineated by classification procedure and given in acres (plate 1).

[3] Estimated from ET rates determined at ET sites (table 7).

[4] Computed as product of ET-unit acreage and ET rate.

Mean annual ground-water discharge from the Ash Meadows area was computed directly from estimates of ET. The computation adjusted the estimated ET rates for each ET unit by removing the local precipitation component. The remaining ET is assumed to be that derived from ground water. Ground-water discharge is estimated by summing adjusted volumetric ET computed for each ET unit as the product of adjusted ET rate and acreage. Different adjustments were applied to account for the uncertainty in (1) the estimate of mean annual precipitation at Ash Meadows, and (2) the percentage of local precipitation included in the computed ET estimate. Although no long-term precipitation data are available for Ash Meadows, a reasonable estimate for mean annual precipitation is between 2.5 and 4.25 inches. This range accounts for differences observed during 3 years of local data collection (volumetric rainfall measurements, fig. 16), long-term record available from four National Weather Service stations in the general area (fig. 16), published maps of precipitation (Hardman, 1965; Winograd and Thordarson, 1975, fig. 3; Houghton and others, 1975, fig. 40), and a map generated by PRISM (parameter-elevation regressions on independent slopes model; Daly and others, 1994).

Three discharge estimates are given in table 11. Each discharge estimate represents a different precipitation adjustment. Estimates were computed with precipitation adjustments of 0, 2.5, and 4.25 inches and range from 18,000 to 21,000 acre-ft. A zero adjustment assumes that ET rates computed from micrometeorological data include no component of precipitation. The 4.25-inch adjustment assumes a high mean annual estimate of precipitation and that all precipitation is included in computed ET rates. The 2.5-inch adjustment represents any one of several of possible scenarios. One scenario would be where mean annual precipitation is 2.5 inches and all precipitation is included in computed ET rates. Another scenario would be where mean annual precipitation is greater than 2.5 inches, but only some portion of the precipitation is included in computed ET rates. The difference between the highest (zero adjustment) and the lowest (4.5-inch adjustment) estimate of ground-water discharge is about 3,000 acre-ft.

Table 11. Estimates of mean annual ground-water discharge from Ash Meadows area, Nevada

[Evapotranspiration (ET) and discharge estimates are rounded.]

Precipitation adjustment [1] (inches)	Adjusted mean annual ET for each ET unit [2] (acre-feet)							Mean ground-water discharge [3] (acre-feet)
	OWB	SAV	DWV	DMV	DGV	SGV	MBS	
0.0	1,400	700	1,500	1,700	5,200	9,300	1,500	21,000
2.5	1,300	680	1,400	1,600	4,900	7,800	1,400	19,000
4.25	1,300	670	1,400	1,500	4,700	6,800	1,300	18,000

[1] Precipitation adjustments span range of estimated mean annual precipitation.

[2] Computed as product of the adjusted ET rate and ET-unit acreage (table 10). Adjusted ET rate computed by subtracting precipitation adjustment from mean annual ET rate. ET-unit identifier is colored to match ET unit as mapped on plate 1. ET units are described in table 3.

[3] Estimated mean ground-water discharge is rounded sum of adjusted mean annual ET computed for each ET unit.

As applied, the precipitation adjustment assumes that the only sources for water being evapotranspired from within the seven classified ET units (areas of substantial ground-water evapotranspiration) are the regional ground-water flow system and rain falling directly on a unit's surface. Although the assumption discounts any water originating from the local infiltration of surface runoff or from precipitation falling on the surface of areas of no substantial ground-water ET (unclassified ET unit) as a potential source, it is considered reasonable in that (1) the water table beneath classified ET units is locally mounded indicating an outward component of ground-water flow, and (2) the limited vertical relief within the general area, the fractured nature of the few lower-lying carbonate-rock ridges, and the low and infrequent rainfall minimize occurrences of surface runoff.

Estimates of mean annual ET and of ground-water discharge (tables 10 and 11) differ some from other estimates reported for the Ash Meadows area. A mean annual ET estimate of 21,000 acre-ft (table 11) falls near the middle of the range defined by previous investigations—11,000 acre-ft (Walker and Eakin, 1963, p. 24; Winograd and Thordarson, 1975, p. 84) to about 35,500 acre-ft (D'Agnese and others, 1997, p. 46). As reported here, annual ET estimates include the Amargosa Flat area (fig. 3). Discrepancies with prior estimates are likely the result of differences in estimates of ET acreage, ET rates, or both. Earlier studies were of a regional scope and had limited data defining local ET rates. Thus, these previous studies applied ET rates for equivalent or similar phreatophytes found elsewhere in the western United States and relied on more general methods for delineating ET acreage. Although the accuracy of one method over another is difficult to evaluate, the more local and rigorous nature of the techniques used in this study suggest a more accurate quantification of ET acreage and rates for the Ash Meadows area.

Most previous estimates of ground-water discharge from the Ash Meadows area are based on measurements of springflow (Winograd and Thordarson, 1975, p. 84). Total springflow from Ash Meadows is estimated to be between 16,500 and 17,500 acre-ft/yr (Walker and Eakin, 1963, p. 24; Dudley and Larson, 1976, p. 12). This range does *not* include water potentially discharging from Amargosa Flat area (fig. 3). However, Winograd and Thordarson (1975, p. 84) calculated the upper limit of annual upward flow from the regional carbonate-rock aquifer into the shallow valley-fill aquifer at Amargosa Flat to be less than 1,000 acre-ft. Assuming that discharge from Amargosa Flat is 1,000 acre-ft (equal to the upper limit of upflow from the regional carbonate aquifer) and adding this quantity to the range estimated for springflow from Ash Meadows proper, total ground-water discharge from the Ash Meadows area would be between 17,500 and 18,500 acre-ft annually. This range is slightly less than that estimated by this study (18,000 to 21,000 acre-ft, table 11). The small difference could be the result of errors in springflow or ET measurements, or could be related to erroneous assumptions in the ET-based method. However, if both estimates are assumed correct, then this difference must be attributed to a source other than springflow that provides water to the shallow valley-fill aquifer. The sources likely to be contributing additional water are diffuse upflow from the regional carbonate-rock aquifer, discharge from subsurface seeps, or some combination thereof.

Limitations of Methodology

The accuracy of the estimate of ground-water discharge is limited by the assumptions inherent in the classification procedure and the energy-budget methods (primarily Bowen ratio) used to compute daily ET. 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; and (4) the uncertainty in the adjustment applied to remove precipitation from ET estimates. The mean annual ET estimate of each ET unit (table 10) was computed from data acquired at three or fewer sites for periods of 2 or less years. The estimate of mean annual precipitation is based on only 3 years of local precipitation measurements. Although the period of data collection did not include an extremely abnormal year, some variation in the annual ET rates was noted 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.

ET-unit acreage was delineated on the basis of TM imagery acquired in 1992. Precipitation data reported for nearby weather stations (fig. 16) indicate that rainfall for 1992 was above normal. To some extent, the above-normal precipitation served as the motivation for selecting 1992 imagery as the means from which to delineate areas of substantial ground-water ET. Years with above-normal precipitation are expected to yield healthier vegetation and moister soils—conditions consistent with easier discrimination by spectral methods. Changes in precipitation have an obvious effect on the vigor and extent of the vegetation, the soil-moisture conditions, and the depth to the water table—all of which effect ET rates. Classifying ET units on the basis of multiple years of imagery would produce acreage estimates more representative of the long-term average.

The procedure classified 10,352 acres of Ash Meadows as an area from which ground water is being lost by evapotranspiration (table 10). The remaining part of Ash Meadows, comprising nearly 40,000 acres, is assumed to be an area of no substantial ground-water loss. This assumption, although strongly supported by the lack of vegetation, dryness of soil, and greater depths to the water table (generally exceeding 15 ft), could result in some error in the estimate of ground-water discharge. Even though ET rates are likely to be small, volumetric losses could be substantial considering the extensive size of area.

The procedure does not identify the open playa of Amargosa Flat (fig. 3) as an area of substantial ground-water ET, but because ground water flows upward from the regional carbonate-rock aquifer into the shallow water table aquifer in this area (Winograd and Thordarson, 1975, p. 84), evaporation of ground water is plausible. The exclusion of the playa acreage from computations of ground-water discharge is presumed reasonable considering the relatively thick low-permeability strata making up the playa sediment and the relatively deep water table (typically more than 15 ft; Kilroy, 1991, fig. 4).

The estimates of ground-water discharge given in table 11 include only water lost through evaporation and transpiration, and do not include any water that may be leaving the Ash Meadows area through subsurface means. Lateral gradients based on two-dimensional configurations of the regional water table (Dudley and Larson, 1976; Kilroy, 1991) indicate a southwest direction of ground-water flow from Ash Meadows into the south-central Amargosa Desert (fig. 2). No rigorous estimates of subsurface outflow into the south-central Amargosa Desert exist within the current literature. Existing estimates are based on regional investigations or on results from regional flow models and range from near zero to a few thousand acre-feet annually (Bateman and others, 1974, p. 5; Czarnecki and Waddell, 1984, table 1; Prudic and others, 1995, p. 62; International Technology Corp., 1997). Until additional data defining water-level distributions and spatial variations in the hydraulic properties controlling ground-water movement throughout the valley-fill and regional carbonate-rock aquifers in south-central Amargosa Desert become available, reliable estimates of subsurface outflow are not possible. Considering the potential for some subsurface outflow and for some ground-water ET from the open playa of Amargosa Flat, the range given for annual ground-water discharge, 18,000 acre-ft to 21,000 acre-ft, should be taken as a minimum estimate of the total ground-water loss from Ash Meadows.

SUMMARY

Ash Meadows is a major area of regional discharge for ground water flowing within Death Valley ground-water flow system of southern Nevada and adjacent California. Although Ash Meadows is situated in an arid region, large quantities of ground water discharge from more than 30 known springs and seeps aligned linearly along the trend of a major fault system. The water emerging from these springs supports a large diversity of vegetation and wildlife and provides habitat for a variety of endangered plant and animal species. Some water flowing from these springs evaporates shortly after emerging, some water flows to pools and reservoirs where it too is evaporated, and the remainder of the water originating as springflow infiltrates downward from drainage channels to recharge the underlying shallow valley-fill aquifer. Moisture held in the local soils and water contained in the shallow valley-fill aquifer sustain thriving populations of local phreatophytes year round. Together these spring features and plant communities create a unique oasis within the expansive, generally barren Mojave Desert.

Ground water discharging at Ash Meadows originates from areas to the north and east and is transported into the area through the regional carbonate-rock aquifer. Discharge at Ash Meadows is continually replenished by ground water derived from an extensive area that includes the eastern part of the Nevada Test Site (NTS). Currently, contaminants introduced into the subsurface by past nuclear testing at the NTS are the subject of the U.S. Department of Energy's Envi-

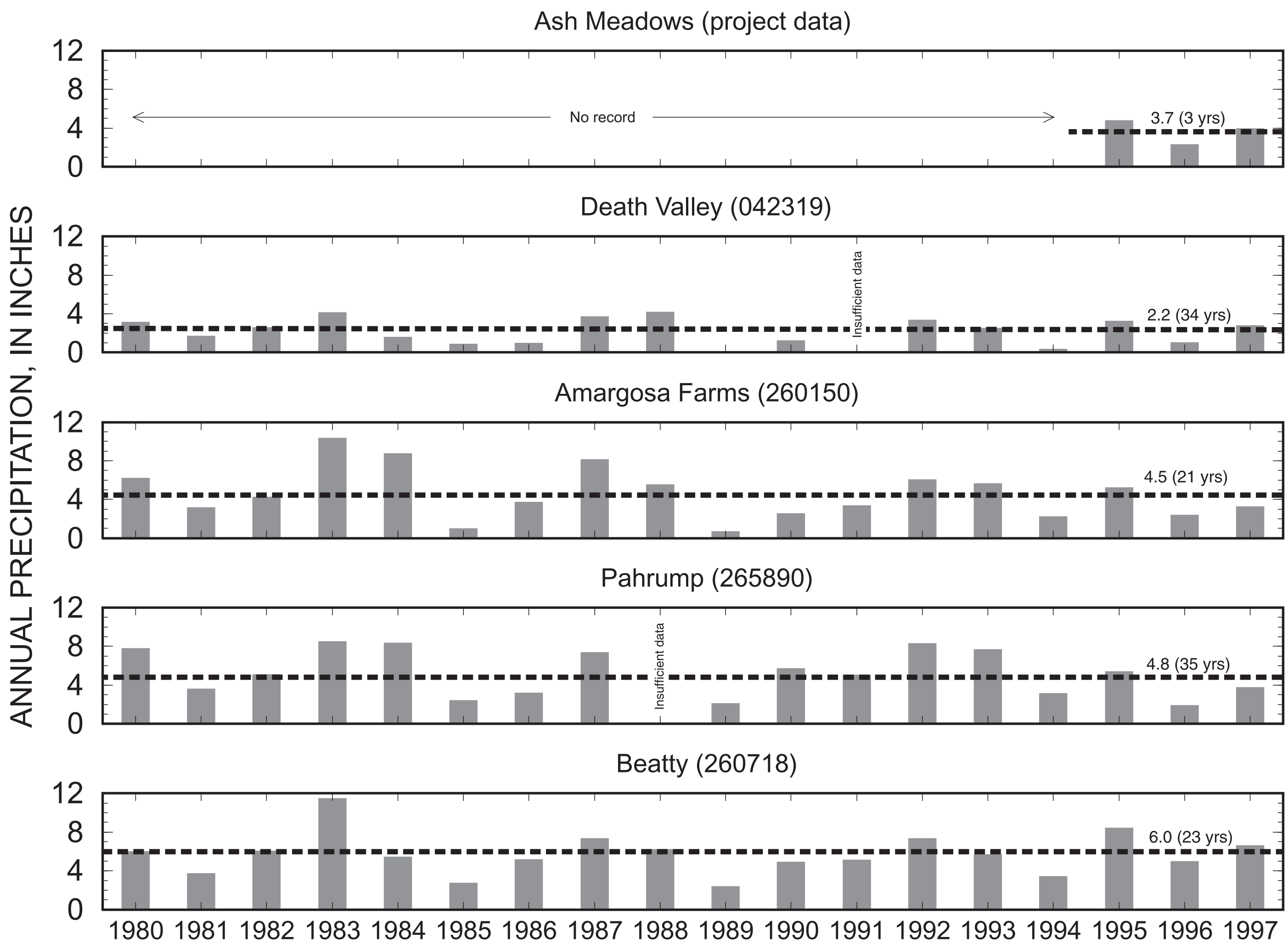


Figure 16. Annual precipitation measured in Ash Meadows and reported at long-term weather stations in general area, 1980-97. Dashed line approximates mean annual precipitation. Number above dashed line is computed mean annual precipitation. Number in parentheses above dashed line is number of years from which mean is computed. Number in parentheses above each plot is National Weather Service station identifier.

ronmental Restoration Program. One requirement of this program is to evaluate the risk that these contaminants pose to the general public. To assess risk, the potential for contaminant transport must be determined. The transport of contaminants residing within the ground water is controlled, in part, by the rate and direction of ground-water flow. The amount of ground water that moves through the subsurface is controlled, in part, by the amount of ground water that leaves the flow system. Because some uncertainty exists as to the amount of ground water discharging downgradient from the NTS, studies have been initiated to re-evaluate and more thoroughly quantify current estimates. This report documents the result of a study to estimate ground-water discharge at Ash Meadows.

Ground-water discharge is estimated through a rigorous quantification of evapotranspiration. This approach assumes that all ground water discharging from the aquifer system beneath Ash Meadows evaporates or transpires locally. Although the approach does not account for springflow directly, it assumes that all springflow evaporates or recycles back into the shallow valley-fill aquifer where later it is transpired or evaporated. Mean annual evapotranspiration from the Ash Meadows area is calculated as the sum of mean annual ET determined for areas of similar vegetation and moisture conditions (referred to as ET units). Mean annual ET for each ET unit is calculated as the product of the unit's acreage and annual ET rate.

Seven unique ET units are defined for the Ash Meadows area on the basis of spectral-reflectance characteristics derived from satellite images recorded in 1992. Six units were delineated by a procedure that combined separate classifications of a June and of a September thematic mapper (TM) image to form a generalized ET-unit map. A third satellite image, an August 1993, SPOT scene, was used to delineate the seventh ET unit by refining identified areas of open water. Together these units encompass about 10,350 acres of sparsely to densely vegetated grassland and wetland. The largest of the seven units, about 7,160 acres, is dominated by sparse, relatively dry grassland, which generally is mixed with shrubs and small trees; and the smallest unit, 81 acres, by submerged aquatic vegetation growing in the shallows and along the shoreline of a few larger open-water bodies.

A mean annual rate of ET is computed for each ET unit from annual ET rates calculated by energy-budget methods (primarily Bowen ratio) at 10 sites instrumented to collect micrometeorological data. Sites are located within six of the seven ET units; 9 of the 10 sites are over land and 1 is over open water. Daily ET rates are computed from micrometeorological measurements averaged for 20-minute periods. Annual ET computed from daily rates determined over a minimum of 1 year ranged from 8.60 ft over an open water site to 0.62 ft over a sparse saltgrass site. Some sites having multiple years of data showed variations in annual ET with precipitation. ET units having the greatest diversity of vegetation and largest contrast in soil-moisture conditions showed the greatest variation in annual ET. Mean annual ET estimates ranged from 8.6 ft for the unit delineating areas of open water to 1.3 ft for the unit delineating areas dominated by sparse grassland vegetation.

Water levels measured in shallow wells within the different ET units show significant annual and daily fluctuations in the water table that are attributed to local water losses associated with evapotranspiration. The largest measured annual water-table fluctuation was 10.2 ft, and the smallest was about 0.4 ft. Smaller annual fluctuations were measured at sites near a constant surface-water source (usually sustained by springflow), whereas, the larger fluctuations were measured at sites in densely vegetated areas most distant from any surface-water source.

In general, measured annual water-table fluctuations are consistent but slightly shifted in time from annual changes in daily ET. The shift is such that the maximum depth to water occurs shortly after ET reaches its maximum rate. Although measured declines are good indicators of ongoing ET, the magnitude of the decline is not always indicative of the rate of ET. Annual water-table declines depend on many other local factors—including the depth of the water table, distance from a surface-water source, aquifer and soil properties, soil-moisture conditions, and precipitation.

The largest measured daily water-table fluctuation is about 0.3 ft at a site dominated by marsh vegetation and standing water. Daily fluctuations typically are larger and in-phase with changing ET rates during periods when the water level is nearest the surface. As water levels drop in response to ET losses, the magnitude of the daily fluctuation attenuates and the daily water-level peak and trough shift from the daily high and low in the ET rate. Water levels measured in deeper (more than 90 ft) wells within ET units and in wells outside ET units generally show smaller (less than 2 ft) responses in the annual water-level fluctuation. These smaller magnitude fluctuations are attributed to processes other than ET, primarily atmospheric loading and earth tides.

Mean annual ET is estimated at 21,000 acre-ft. An estimate of the mean annual ground-water discharge, based solely on ET, is presented as a range to account for uncertainties in the contribution of local precipitation. Annual ET rates determined for each ET unit were adjusted to remove any contribution by local precipitation from the ET estimate. Adjustments of 0, 2.5, and 4.25 inches are applied to span the range of the potential precipitation contribution. Mean annual precipitation is estimated between 2.5 and 4.25 inches. Assuming a zero adjustment (no local precipitation contribution), the estimate of the mean annual discharge is 21,000 acre-ft. Assuming a 4.25-inch adjustment (the maximum precipitation contribution), the estimate of mean annual ground-water discharge is 18,000 acre-ft.

Estimates of mean annual ET fall near the middle of the range defined by previous estimates—11,000 acre-ft (Walker and Eakin, 1963, p. 24; Winograd and Thordarson, 1975, p. 84) to about 35,500 acre-ft (D'Agnese and others, 1997, p. 46). Although the accuracy of one method over another is difficult to evaluate, the more local and rigorous character of the techniques used in this study suggest a more accurate quantification of ET acreage and rates upon which the mean annual estimate is based. The range given for ground-water discharge is slightly greater than that estimated previously for Ash Meadows primarily on the basis of springflow measurements. The small difference might be the result of errors, either in springflow measurements or in measurements of the micrometeorological data required to compute ET, or the result of erroneous assumptions in the classification procedure or in the Bowen ratio solution. But if both estimates are assumed reasonably accurate, the higher ET-based estimate can be attributed to another water source helping sustain the shallow water table. Likely sources for the additional inflow are diffuse upflow from the underlying regional carbonate aquifer or discharge from subsurface seeps.

The accuracy of the estimate of ground-water discharge is limited by the assumptions inherent in the classification procedure, the energy-budget methods (primarily Bowen ratio) used to compute daily ET, and the averaging techniques applied to estimate mean annual ET. 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 data used to compute mean values; (3) the limited number of sites used to estimate ET for each ET unit; and (4) the uncertainty in the amount of local precipitation included in the computed ET rates. Multiyear classifications, longer term data acquisition, and a greater number of local ET-site installations would help refine, improve, and provide more confidence in the estimate of mean annual ground-water discharge.

The estimate of ground-water discharge presented includes only water lost through evaporation and transpiration and does not include any water that may be leaving the Ash Meadows area through subsurface means. Assuming some potential for subsurface outflow, the range given for annual ground-water discharge should be considered a minimum value of total outflow from the Ash Meadows area.

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SUPPLEMENTAL DATA

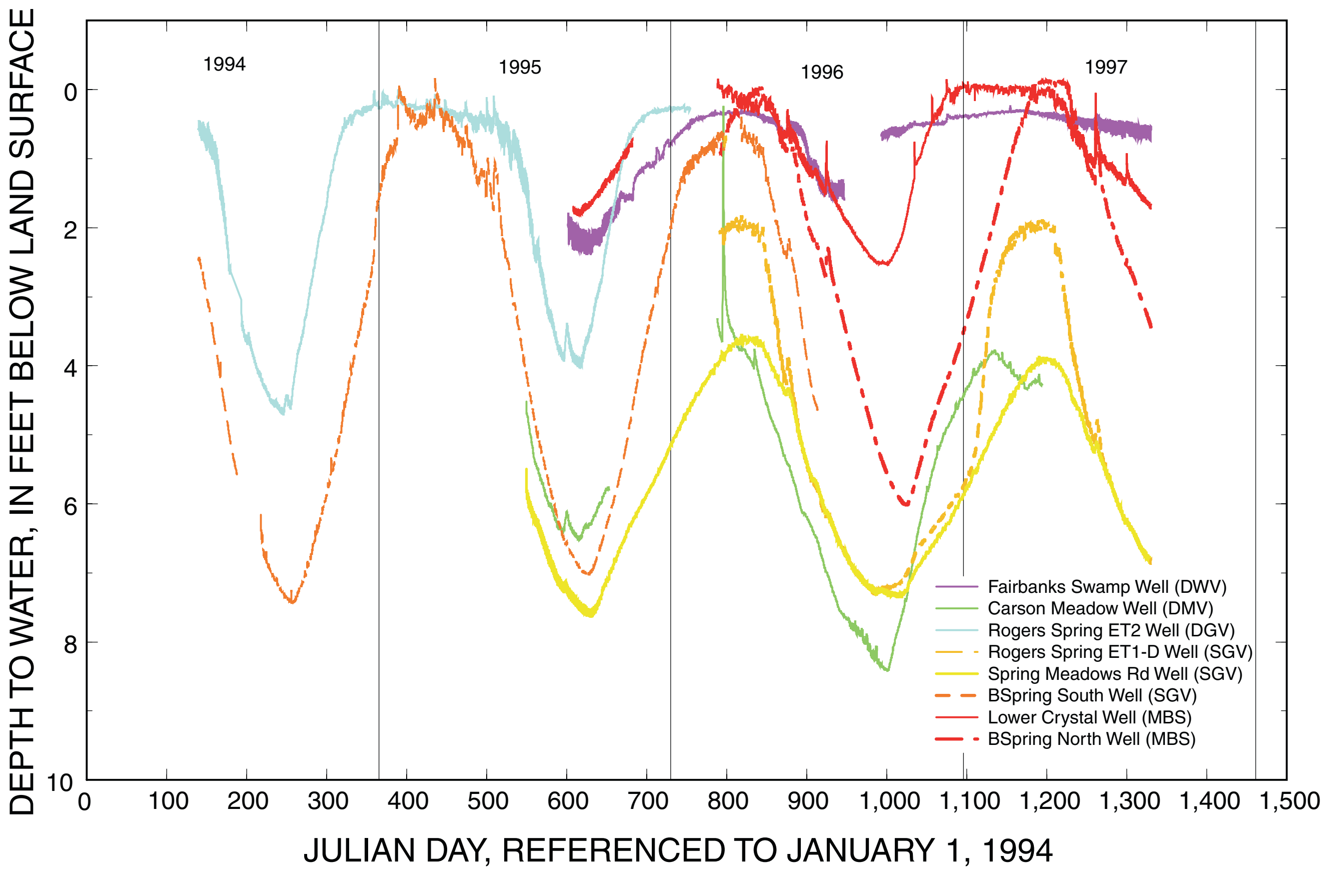

Figure 17. Water-table fluctuations measured at evapotranspiration (ET) sites, May 19, 1994, to August 23, 1997. ET-unit acronyms (in parentheses) are explained in table 3.

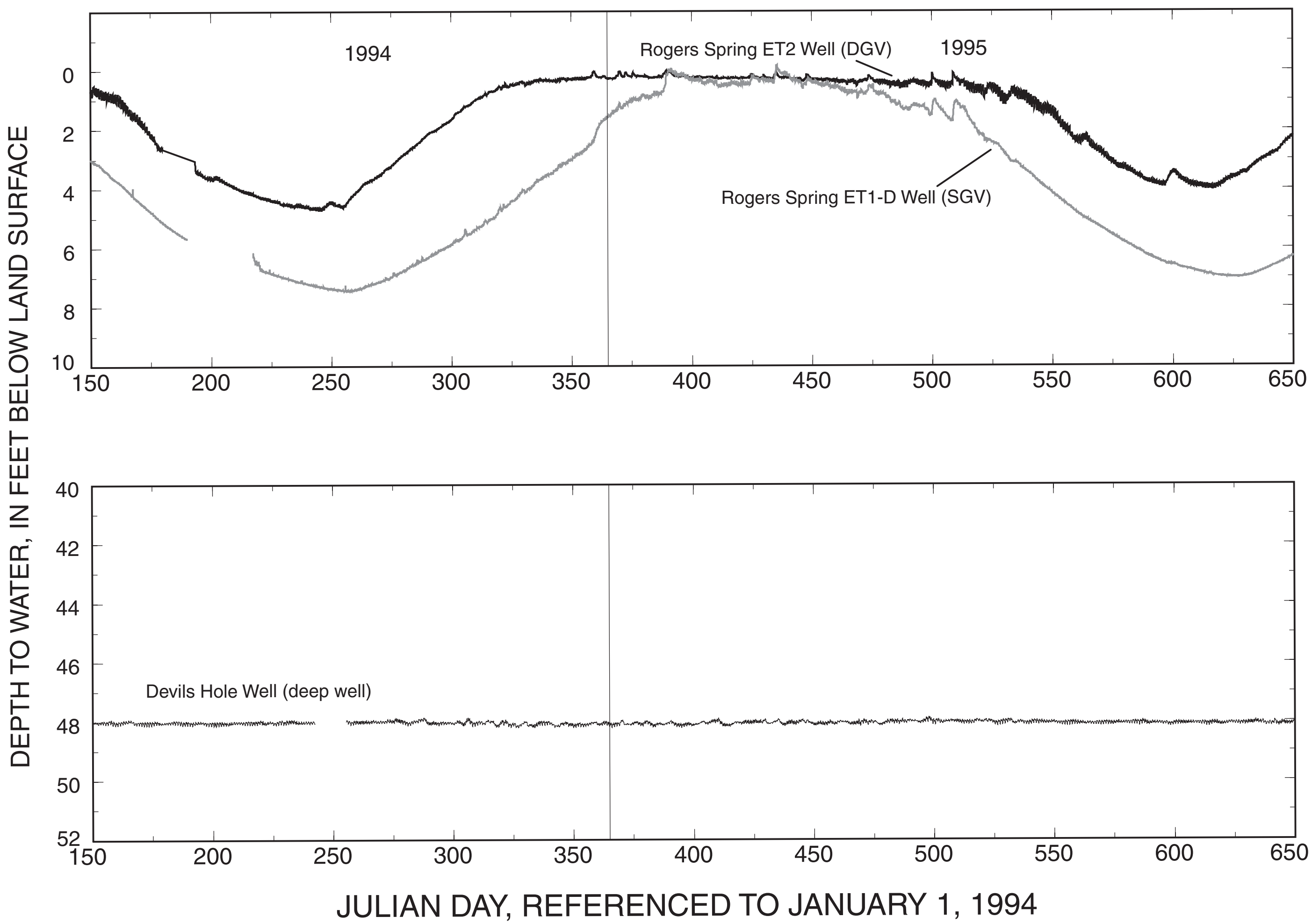

Figure 18. Annual water-level fluctuation in a deep well and two shallow wells, May 5, 1994, to October 9, 1995. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

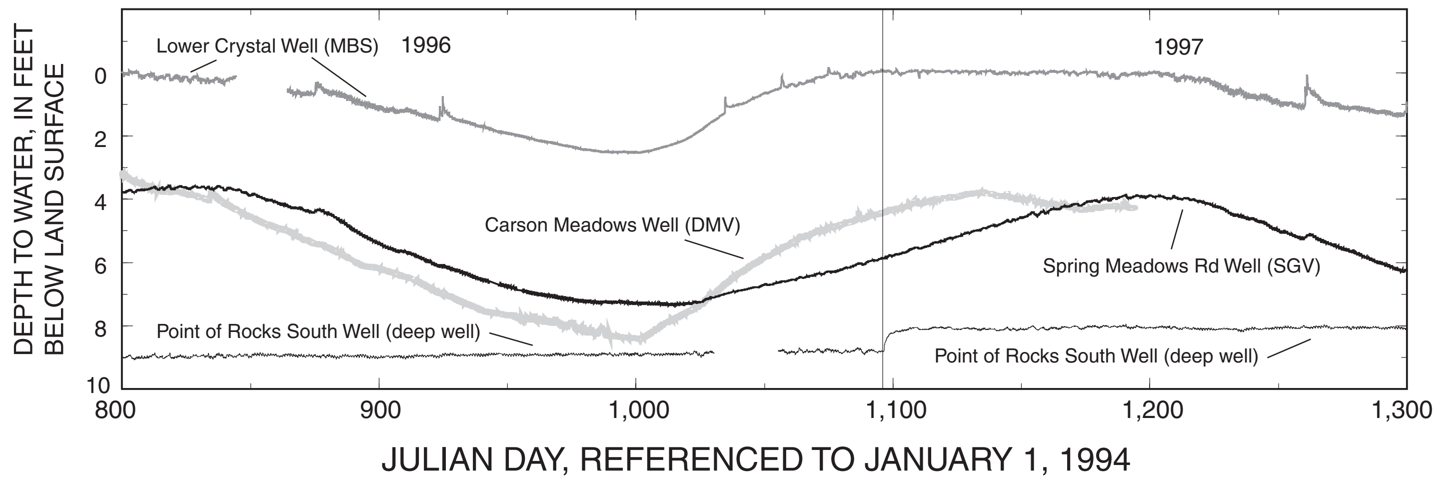

Figure 19. Annual water-level fluctuation in selected deep and shallow wells, March 10, 1996, to July 22, 1997. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

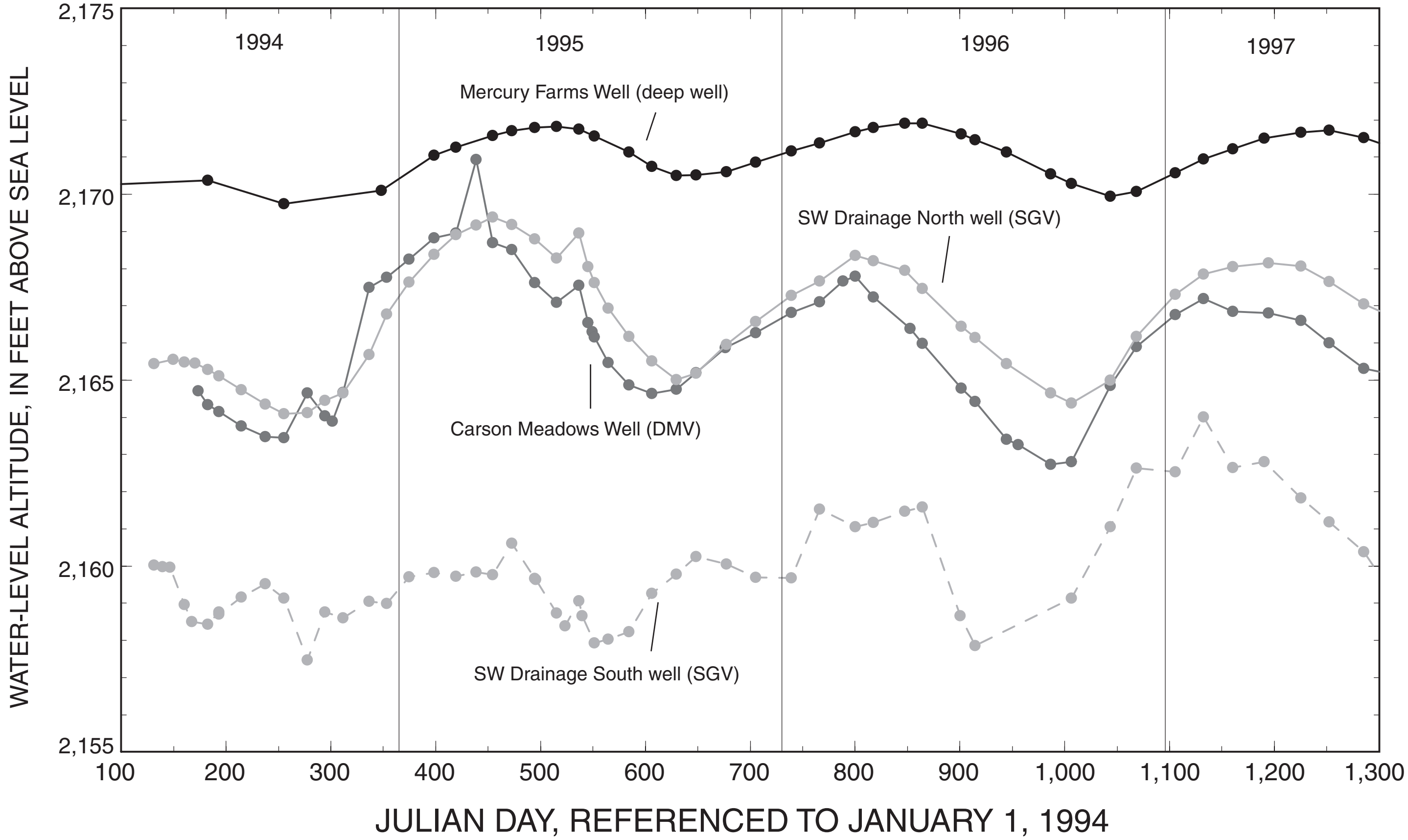

Figure 20. Annual water-level fluctuation in selected deep and shallow wells, April 10, 1994, to July 22, 1997. Circle represents periodic water-level measurement. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

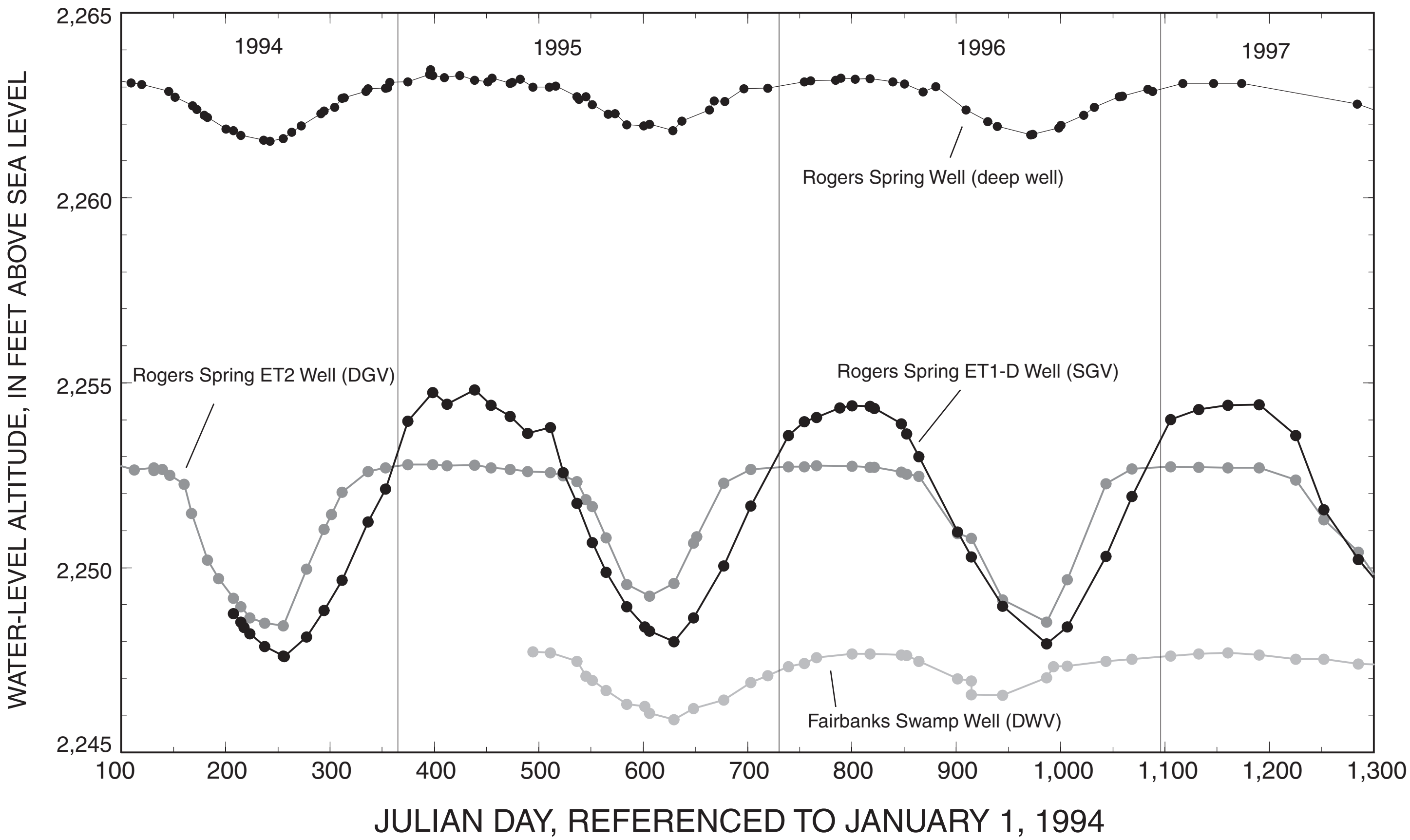

Figure 21. Annual water-level fluctuation in selected deep and shallow wells, April 10, 1994, to July 22, 1997. Circle represents periodic water-level measurement. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

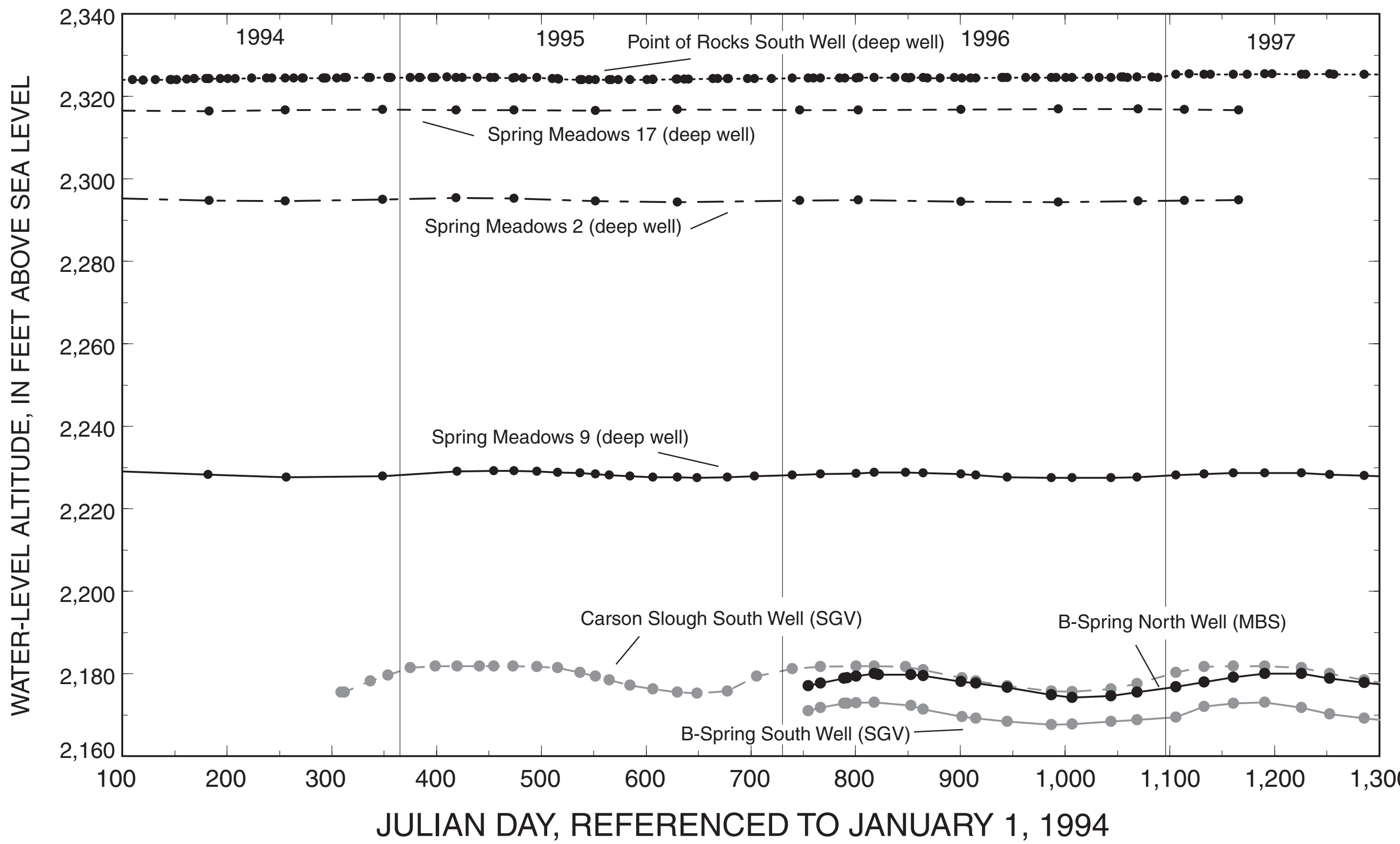

Figure 22. Annual water-level fluctuation in selected deep and shallow wells, April 10, 1994, to July 22, 1997. Circle represents periodic water-level measurement. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

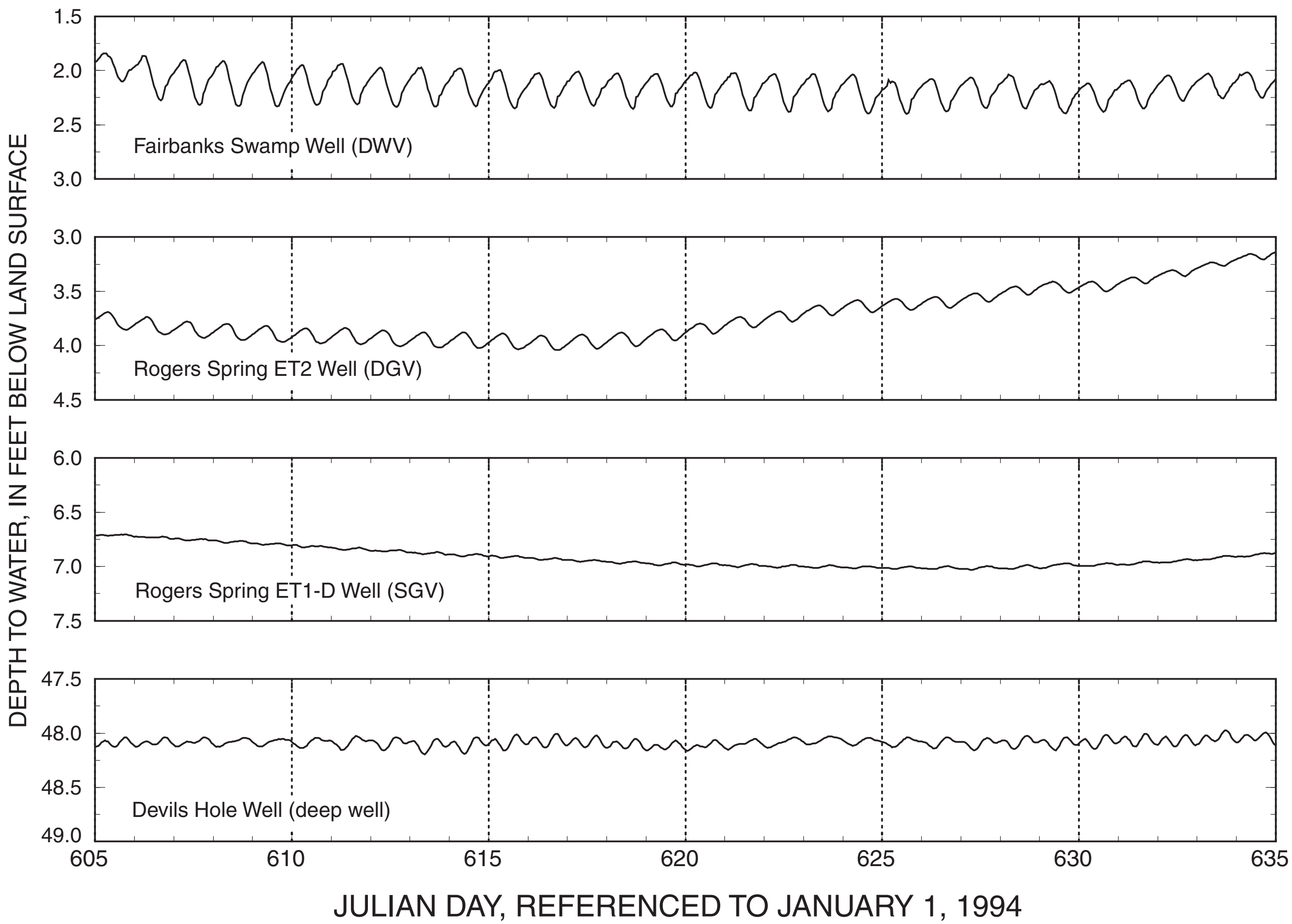

Figure 23. Daily water-level fluctuation at selected deep and shallow wells, August 28 to September 26, 1995. Text in parentheses identifies associated ET unit or general well type (see table 3 for description of ET units).

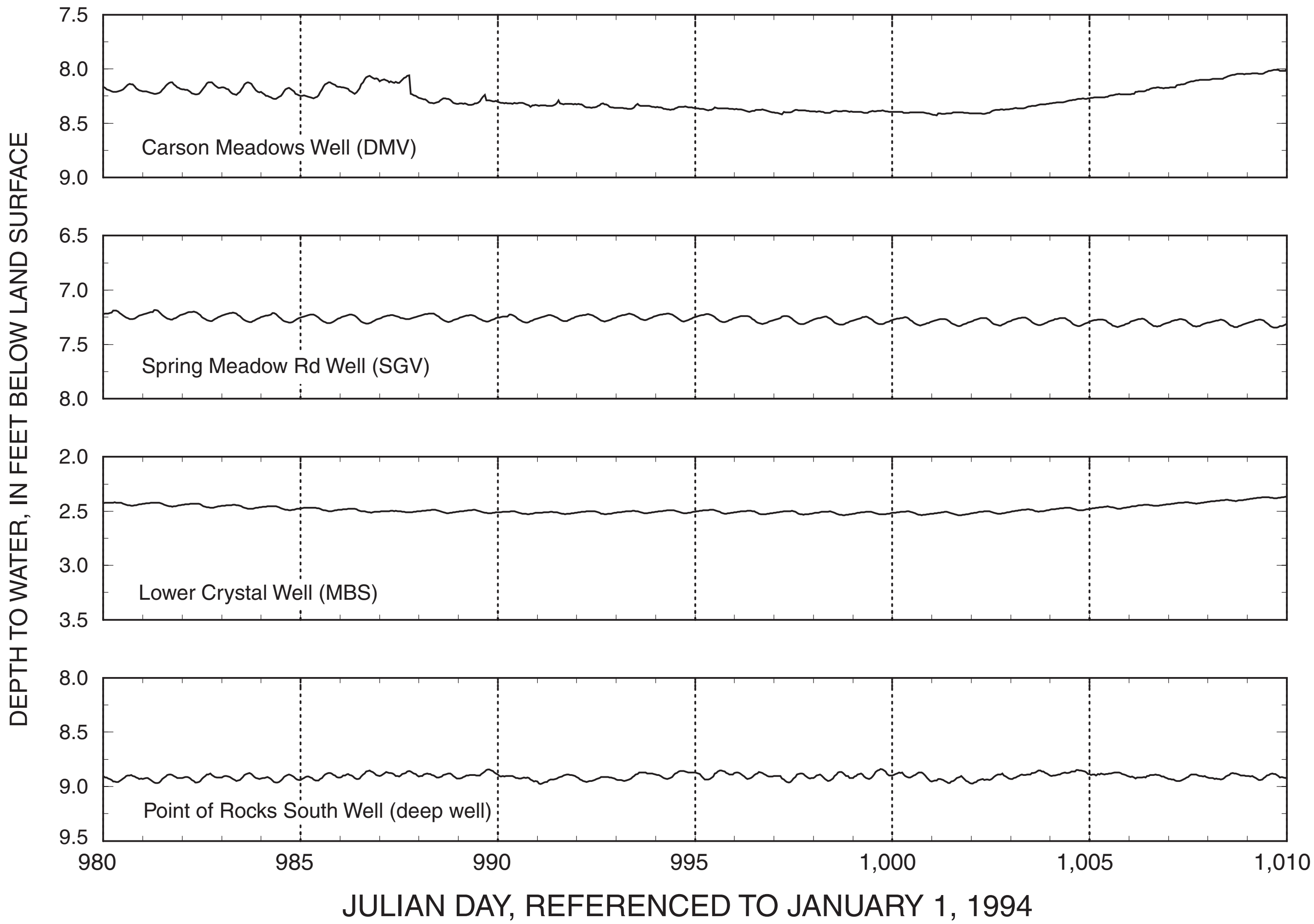

Figure 24. Daily water-level fluctuation at selected deep and shallow wells, September 7 to October 6, 1996. Text in parentheses identifies ET unit or general well type (see table 3 for description of ET units).

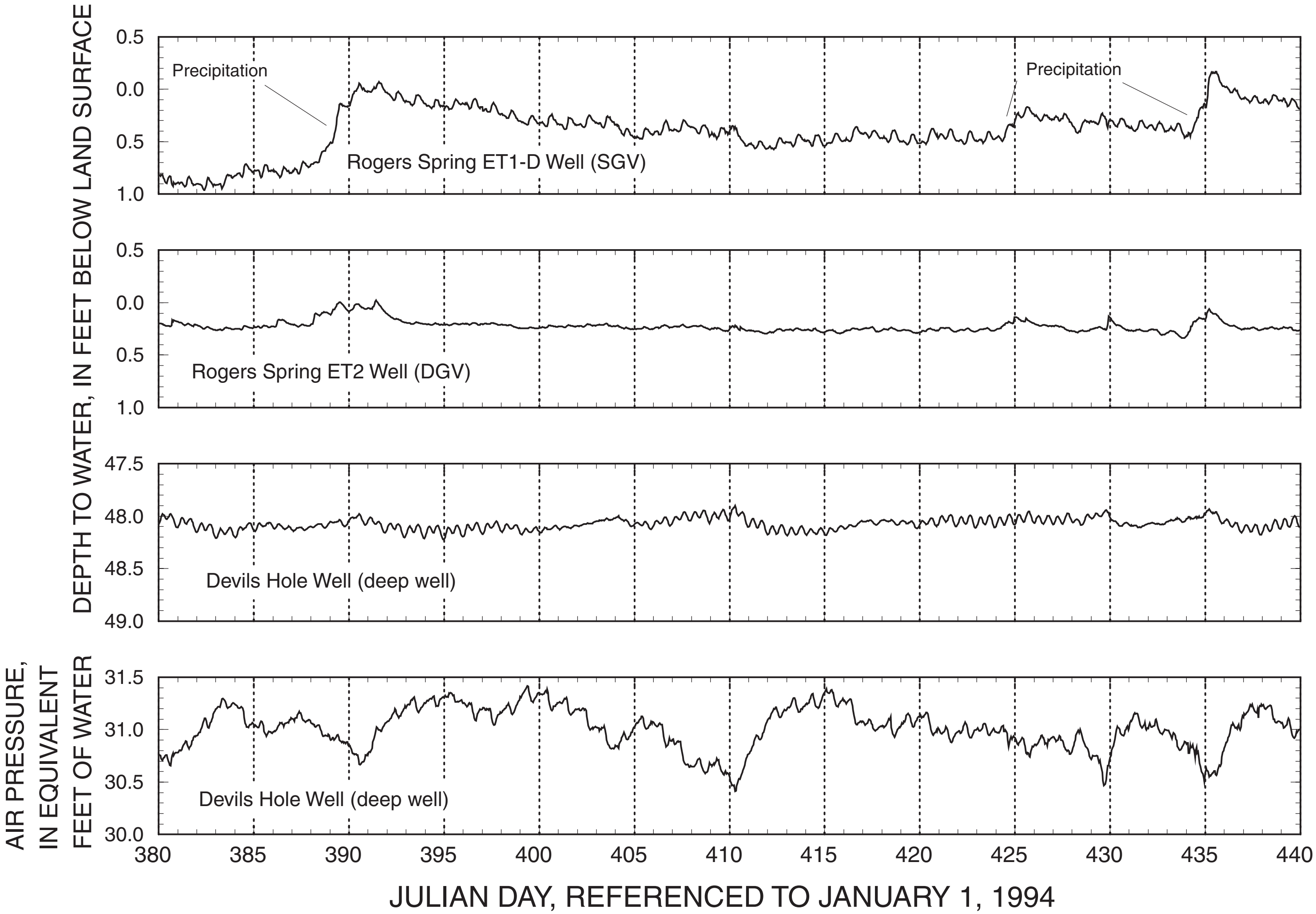

Figure 25. Air pressure and daily water-level fluctuations in selected deep and shallow wells, January 15 to March 15, 1995. Graph shows water-level response to precipitation and air pressure changes. Text in parentheses identifies ET unit or general well type (see table 3 for description of ET units).

Table 12. Shallow wells installed and measured during study, Ash Meadows area, Nevada

Well name: Names listed in alphabetical order. All CS wells installed and measured by U.S. Fish and Wildlife Service.

U.S. Geological Survey site identification number: A unique 15-digit number based on a latitude-longitude grid. The first six digits denote degrees, minutes, and seconds of latitude, the next seven digits denote degrees, minutes, and seconds of longitude, and the last two digits denote a unique sequence number within a 1-second grid of latitude and longitude.

Local site number: Alphanumeric identifier based on location of site within hydrographic areas and rectangular subdivisions of public lands.

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

Well depth: Datum is land surface. Well depths sounded by U.S. Geological Survey personnel.

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.

ET (evapotranspiration) unit: DGV, dense grassland vegetation; DMV, dense meadow vegetation; DWV, dense wetland vegetation; MBS, moist bare soil; OWB, open-water body; SAV, submerged aquatic vegetation; SGV, sparse grassland vegetation; and UCL, unclassified. See table 3 for more detailed description of ET units.

Nearby hydrographic feature: Hydrographic feature in vicinity of site that holds or transports surface water and may affect the measured water level. Double dash indicates no nearby feature.

Well name	U.S. Geological Survey site identification number	Latitude (degree, minutes, seconds)	Longitude (degrees, minutes, seconds)	Local site number	Land-surface altitude (feet)	Well depth (feet)	Depth to open interval		Type of open interval	ET unit	Nearby hydrographic feature
							Top (feet)	Bottom (feet)			
Amargosa Flat Playa Well	362936116153001	362936	1161530	230 S17 E51 08ABC 1	2,322	14.5	9.1	14.1	P	UCL	Dry playa lake
American Resources Well	362148116175701	362148	1161757	230 S18 E50 25BBB 1	2,190	9.7	4.3	9.3	P	DGV	--
Ash Forest Well[1]	362402116190501	362402	1161905	230 S18 E50 12CBC 1	2,183	8.5	3.2	8.2	P	SGV	Manmade reservoir
B-Spring North Well[1]	362236116281101	362227	1161811	230 S18 E50 23ADD 1	2,180	13.2	8.2	13.2	P	MBS	--
B-Spring South Well[1]	362214116181601	362214	1161817	230 S18 E50 23DAB 1	2,175	14.1	6.7	13.8	P	SGV	Intermittent drainage
Big Spring Well	362227116163101	362227	1161631	230 S18 E51 19BDA 1	2,240	9.25	3.9	8.9	P	SGV	Perennial spring drainage
Carson Meadows Well[1]	362515116202001	362515	1162020	230 S18 E50 04ADA 1	2,171	10.9	5.5	10.5	P	DMV	--
Carson Slough 3 Well	362531116214901	362531	1162149	230 S17 E50 32DCC 1	2,133	13.25	8.25	13.1	P	SGV	Intermittent drainage
Carson Slough South Well	362217116180801	362207	1161807	230 S18 E50 23DDA 1	2,182	12.35	7.0	12.0	P	SGV	Intermittent drainage
Carson Slough Terrace Well	362531116214701	362531	1162147	230 S17 E50 32DCC 2	2,136	12.7	7.3	12.3	P	SGV	Intermittent drainage
Carson West Well	362709116221101	362709	1162211	230 S17 E50 29BBA 1	2,153	17.8	9.8	17.45	P	SGV	--
Cold Spring Well	362743116205101	362743	1162051	230 S17 E50 21BDD 1	2,207	17.35	12.0	17.0	P	DMV	--
CS-01 Well	362859116203102	362858	1162033	230 S17 E50 09DDC 2	2,242	10.7	8.2	10.7	P	DGV	--
CS-02 Well	362901116203501	362859	1162036	230 S17 E50 09DDB 1	2,240	11.5	9.5	11.5	P	SGV	
CS-03 Well	362901116203701	362900	1162037	230 S17 E50 09DDB 2	2,240	8.4	6.3	8.4	P	DMV	--

Table 12. Shallow wells installed and measured during study, Ash Meadows area, Nevada—Continued

Well name	U.S. Geological Survey site identification number	Latitude (degree, minutes, seconds)	Longitude (degrees, minutes, seconds)	Local site number	Land-surface altitude (feet)	Well depth (feet)	Depth to open interval		Type of open interval	ET unit	Nearby hydrographic feature
							Top (feet)	Bottom (feet)			
CS-04 Well	362854116204001	362850	1162040	230 S17 E50 16ABA 1	2,240	11.0	8.6	11.0	P	SGV	--
CS-05 Well	362855116204401	362854	1162042	230 S17 E50 16ABB 1	2,237	13.5	8.8	13.5	P	DGV	--
CS-06 Well	362855116204901	362854	1162044	230 S17 E50 16ABB 2	2,240	13.2	11.2	13.2	P	DMV	--
CS-07 Well	362842116205101	362842	1162050	230 S17 E50 16BDA 1	2,231	17.4	14.9	17.4	P	DGV	--
CS-08 Well	362844116205601	362843	1162056	230 S17 E50 16BAD 1	2,228	20.0	17.5	20.0	P	DGV	--
CS-09 Well	362847116205601	362846	1162058	230 S17 E50 16BAD 2	2,229	20.0	18.2	20.0	P	DMV	--
CS-10 Well	362840116210901	362832	1162106	230 S17 E50 16BCA 1	2,224	20.0	17.5	20.0	P	DMV	--
CS-11 Well	362827116211101	362825	1162109	230 S17 E50 16CBA 1	2,219	15.5	13.3	15.5	P	DMV	--
CS-12 Well	362818116211401	362817	1162113	230 S17 E50 16CBD 1	2,218	11.3	9.0	11.3	P	DMV	--
Fairbanks Swamp Well [1]	362902116202201	362902	1162022	230 S17 E50 09DDA 1	2,248	8.25	2.9	7.9	P	DWV	Perennial spring drainage
F-Meadows Well	362859116201901	362859	1162019	230 S17 E50 10CC 1	2,249	6.8	3.4	6.6	P	DGV	--
Lower Crystal Well[1]	362421116200701	362421	1162007	230 S18 E50 10BCB 1	2,148	12.0	3.8	11.65	P	MBS	Marsh/lake drainage
Peterson Reservoir Well	362639116205801	362639	1162058	230 S17 E50 28CAC 1	2,162	10.7	3.1	10.4	P	SGV	Manmade reservoir
Rogers Spring ET1 Well	362855116200701	362852	1162004	230 S17 E50 10BBA 1	2,255	6.25	3.5	5.75	P	SGV	--
Rogers Spring ET1-D Well[1, 2]	362855116200702	362852	1162004	230 S17 E50 10BBA 2	2,255	10.0	2.3	9.6	P	SGV	--
Rogers Spring ET2 Well[1]	362856116195601	362856	1161956	230 S17 E50 10CD 1	2,253	5.8	3.6	5.8	P	DGV	--
Spring Meadows Rd Well[1]	362536116211801	362536	1162118	230 S17 E50 33CCC 1	2,140	14.2	8.8	13.8	P	SGV	--
SW Drainage North Well	362519116201301	362519	1162013	230 S18 E50 03BBC 1	2,175	14.5	9.45	14.45	P	SGV	--
SW Drainage South Well[1]	362450116201401	362450	1162014	230 S18 E50 04DDA 1	2,166	9.75	6.75	9.75	P	SGV	Manmade drainage diversion

[1] Well instrumented for continual data collection.

[2] Replacement well for Rogers Spring ET1.

Table 13. Existing wells measured during study, Ash Meadows area, Nevada

Well name: Names listed in alphabetical order.

U.S. Geological Survey site identification number: A unique 15-digit number based on a latitude-longitude grid. The first six digits denote degrees, minutes, and seconds of latitude, the next seven digits denote degrees, minutes, and seconds of longitude, and the last two digits denote a unique sequence number within a 1-second grid of latitude and longitude.

Local site number: Alphanumeric identifier based on location of site within hydrographic areas and rectangular subdivisions of public lands.

Land-surface altitude: Datum is sea level. Altitudes are reported to nearest foot and were estimated from U.S. Geological Survey 1:24,000 topographic maps. Altitudes reported to nearest tenth of a foot obtained from leveling surveys.

Well depth: Datum is land surface. Well depths sounded by U.S. Geological Survey personnel or as reported in drilling logs provided to Nevada Division of Water Resources.

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; X, open hole.

ET (evapotranspiration) unit: DGV, dense grassland vegetation; DMV, dense meadow vegetation; DWV, dense wetland vegetation; MBS, moist bare soil; OWB, open-water body; SAV, submerged aquatic vegetation; SGV, sparse grassland vegetation; and UCL, unclassified. See table 3 for more detailed description of ET units.

Contributing lithologic unit: Lithologic unit(s) present at interval yielding water to the well. Carb. rx., carbonate rock.

[Data sources for construction and location information include Dudley and Larson (1976), La Camera and Westenburg (1994), Hale and Westenburg (1995), La Camera and others (1996), Westenburg and La Camera (1996), La Camera and Locke (1997), and the Nevada Division of Water Resources drilling logs. Dash indicates no information or acts as placeholder.]

Well name	U.S. Geological survey site identification number	Latitude (degree, minutes, seconds)	Longitude (degrees, minutes, seconds)	Local site number	Land-surface altitude (feet)	Well depth (feet)	Depth to open interval: Top (feet)	Depth to open interval: Bottom (feet)	Type of open interval	ET unit	Contributing lithologic unit
Amargosa Flat Corral Well	362736116123201	362744	1161243	230 S17 E51 23BCB 1	2,328.3	25	-	-	-	UCL	Valley fill
Buck Mining Hand Dug Well	362738116104701	362738	1161047	230 S17 E51 24ADDC2	2,365	19.4	0	19.4	X	UCL	Valley fill
Buck Mining Windmill Well	362740116112601	362738	1161049	230 S17 E51 24ADDC1	2,365	22	0	22	X	UCL	Valley fill
Devils Hole Well [1]	362529116171100	362530	1161715	230 S17 E50 36DDC 1	2,404.1	200	48	248	P	UCL	Valley fill
Five Springs Well	362755116190401	362755	1161904	230 S17 E50 23BBCA1	2,367.4	123	0	100	P	DGV	Carb. rx.
							100	140	X		
Five Springs Shallow Well	362755116190402	362755	1161904	230 S17 E50 23BBCA2	2,367	90	0	90	P	DGV	Carb. rx.
Garners Well	362555116205301	362555	1162053	230 S17 E50 33CAAB1	2,157.0	202	140	180	P	SGV	Valley fill
GS-1 Well	362014116133901	362021	1161330	230 S18 E51 34CBD 1	2,430.3	1,580	1,549	1,559	S	UCL	Valley fill
GS-02 Deep	362113116160101	362103	1161600	230 S18 E51 30DDD 1	2,295	1,197	1,166	1,176	P	UCL	Valley fill
GS-02 Shallow	362113116160102	362103	1161600	230 S18 E51 30DDD 2	2,295	120	117	120	P	UCL	Valley fill

Table 13. Existing wells measured during study, Ash Meadows area, Nevada—Continued

Well name	U.S. Geological survey site identification number	Latitude (degree, minutes, seconds)	Longitude (degrees, minutes, seconds)	Local site number	Land-surface altitude (feet)	Well depth (feet)	Depth to open interval		Type of open interval	ET unit	Contributing lithologic unit
							Top (feet)	Bottom (feet)			
IMV Bentonite Mine Well	363157116221201	363153	1162216	230 S16 E50 29ACD 1	2,374	100	-	-	-	UCL	Valley fill
IMV Borehole	362303116174502	362303	1161745	230 S18 E50 13CAC 2	2,220	15	0	15	X	UCL	Valley fill
Mercury Farms Well	362554116204001	362536	1162022	230 S17 E50 33DDD 1	2,178	100	60	120	P	SGV	Valley fill
Mine Shaft	362755116202001	362755	1162020	230 S17 E50 21AAD 1	2,257	57	0	57	X	UCL	Valley fill
MSH-C Deep Well	363008116161201	363008	1161612	230 S17 E51 06ADD 1	2,330	1,669.41	1,519.10	1,636.38	P	UCL	Valley fill
MSH-C Shallow Well	363008116161202	363008	1161612	230 S17 E51 06ADD 2	2,330	347	281	314	P	UCL	Valley fill
Peterson Well	362648116201401	362648	1162014	230 S17 E50 28DAA 1	2,215	450	90	450	P	UCL	Valley fill
Point of Rocks North Well	362432116165701	362432	1161657	230 S18 E51 07BBBB1	2,318.8	500	139	500	P	UCL	Valley fill
Point of Rocks South Well[1]	362417116163600	362420	1161637	230 S18 E51 07BDB 1	2,333.5	586	132	467	P	UCL	Valley fill
							468	818	X		Carb. rx.
Rogers Spring Well	362858116195301	362855	1161950	230 S17 E50 10CDD 1	2,265.9	202	100	240	P	DGV	Valley fill
Rogers Spring Well 2	362858116195302	362857	1161947	230 S17 E50 10DCC 1	2,267	332	40	332	P	UCL	Valley fill
Spring Meadows 1	362410116160901	362405	1161552	230 S18 E51 08CBB 1	2,321	395	155	395	P	SGV	Valley fill
Spring Meadows 2	362409116155601	362357	1161605	230 S18 E51 07DAC 1	2,308	415	0	415	P	SGV	Valley fill
Spring Meadows 3	362358116160101	362352	1161552	230 S18 E51 08CCB 1	2,308	780	10	780	P	SGV	Valley fill
Spring Meadows 4	362358116163301	362404	1161630	230 S18 E51 07CAA 1	2,304	500	100	500	P	DGV	Valley fill
Spring Meadows 6	362514116192001	362518	1161913	230 S18 E50 03AAD 1	2,205	516	-	-	-	DMV	Valley fill
Spring Meadows 9	362425116181001	362434	1161811	230 S18 E50 11AAA 1	2,248	280	82	280	P	UCL	Valley fill
Spring Meadows 11	362521116160801	362521	1161608	230 S18 E51 06AAC 1	2,442	215	-	-	-	UCL	Valley fill
Spring Meadows 12	362529116160501	362527	1161608	230 S18 E51 06AAB 1	2,433	265	-	-	-	UCL	Valley fill
Spring Meadows 16	362408116154001	362405	1161545	230 S18 E51 08CBA 2	2,328	642	0	642	P	SGV	Valley fill
Spring Meadows 17	362406116154001	362405	1161539	230 S18 E51 08CBA 1	2,325	500	100	500	P	SGV	Valley fill
Trenary Well	362505116223001	362802	1162239	230 S17 E50 19AAB 1	2,185	100	15	100	P	UCL	Valley fill
White Well	363030116104501	363031	1161047	230 S17 E51 01AAAB1	2,403	135	60	135	P	UCL	Valley fill
							240	420	X		

[1] Well instrumented for continual data collection.