U.S. Department of the Interior
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Estimated Ground-Water Discharge by Evapotranspiration from Death Valley, California, 1997–2001

Water-Resources Investigations Report 03-4254

Prepared in cooperation with the
U.S. DEPARTMENT OF THE INTERIOR,
NATIONAL PARK SERVICE and
INYO COUNTY, CALIFORNIA

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By Guy A. DeMeo, Randell J. Laczniak, Robert A. Boyd,
J. LaRue Smith, and Walter E. Nylund

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Carson City, Nevada
2003

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	square hectometer
square mile (mi^2)	2.590	square kilometers
	Volume	
acre-foot (acre-ft)	0.001233	cubic hectometer
	Energy Flux	
Watt per square foot (W/ft^2)	10.76	Watt per square meter
	Pressure	
pounds per square inch (lb/in^2)	6.895	kilopascal
	Velocity or Rate	
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
foot per second (ft/s)	0.3048	meter 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:

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = (1.8 × °C) + 32. Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by using the formula °C = 0.556(°F-32). Temperature in degrees kelvin (°K) can be converted to degrees Fahrenheit (°F) by using the formula °K = (°F+459.67)/1.8.

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

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

Symbols and Acronym

C_p	Specific heat of air at a constant pressure
DVRFS	Death Valley regional ground-water flow system
E	Rate of water-vapor flux
$e_{l,u}$	Vapor pressure at lower or upper reference point
ET	Evapotranspiration
ET_{gw}	Component of evapotranspiration from ground water
G	Soil-heat flux
GPS	Global Positioning System
H	Sensible-heat flux
k_h	Turbulent transfer coefficient of heat in air
k_v	Turbulent transfer coefficient of vapor
L	Soil-adjustment factor
MSAVI	Modified soil-adjusted vegetation index
NPS	National Park Service
NWI	National Wetland inventory
NWS	National Weather Service
P	Ambient air (barometric) pressure
p	Annual local precipitation
R_n	Net radiation
S_w	Ground- or surface-water accumulation resulting from flooding or precipitation
T	Air temperature
T'	Instantaneous deviation of air temperature from the mean
$T_{l,u}$	Air temperature at lower or upper reference point
THPs	Temperature-humidity probes
TM	Thematic mapper
USGS	U.S. Geological Survey
w'	Instantaneous deviation of vertical wind speed from the mean
$z_{l,u}$	Lower and upper reference heights of air temperature and vapor pressure
β	Bowen ratio
ε	Ratio of molecular weight of water vapor to dry air
γ	Psychrometric constant
λ	Latent heat of vaporization for water
λE	Latent-heat flux
ρ_v'	Instantaneous deviation of water vapor from the mean
ρ_a	Density of air
ρ_w	Density of water

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ABSTRACT

The U.S. Geological Survey, in cooperation with the National Park Service and Inyo County, Calif., collected field data from 1997 through 2001 to accurately estimate the amount of annual ground-water discharge by evapotranspiration (ET) from the floor of Death Valley, California.

Multispectral satellite-imagery and National Wetlands Inventory data are used to delineate evaporative ground-water discharge areas on the Death Valley floor. These areas are divided into five general units where ground-water discharge from ET is considered to be significant. Based upon similarities in soil type, soil moisture, vegetation type, and vegetation density; the ET units are salt-encrusted playa (21,287 acres), bare-soil playa (75,922 acres), low-density vegetation (6,625 acres), moderate-density vegetation (5,019 acres), and high-density vegetation (1,522 acres). Annual ET was computed for ET units with micrometeorological data which were continuously measured at six instrumented sites. Total ET was determined at sites that were chosen for their soil- and vegetated-surface conditions, which include salt-encrusted playa (extensive salt encrustation) 0.17 feet per year, bare-soil playa (silt and salt encrustation) 0.21 feet per year, pickleweed (pickleweed plants, low-density vegetation) 0.60 feet per year, Eagle Borax (arrowweed plants and salt grass, moderate-density vegetation) 1.99 feet per year, Mesquite Flat (mesquite trees, high-density vegetation) 2.86 feet per year, and Mesquite Flat mixed grasses (mixed meadow grasses, high-density vegetation) 3.90 feet per year.

Precipitation, flooding, and ground-water discharge satisfy ET demand in Death Valley. Ground-water discharge is estimated by deducting local precipitation and flooding from cumulative ET estimates.

Discharge rates from ET units were not estimated directly because the range of vegetation units far exceeded the five specific vegetation units that were measured. The rate of annual ground-water discharge by ET for each ET unit was determined by fitting the annual ground-water ET for each site with the variability in vegetation density in each ET unit. The ET rate representing the midpoint of each ET unit was used as the representative value. The rate of annual ground-water ET for the playa sites did not require scaling in this manner. Annual ground-water discharge by ET was determined for all five ET units: salt-encrusted playa (0.13 foot), bare-soil playa (0.15 foot), low-density vegetation (1.0 foot), moderate-density vegetation (2.0 feet), and high-density vegetation (3.0 feet), and an area of vegetation or bare soil not contributing to ground-water discharge unclassified (0.0 foot).

The total ground-water discharge from ET for the Death Valley floor is about 35,000 acre-feet and was computed by summing the products of the area of each ET unit multiplied by a corresponding ET rate for each unit.

INTRODUCTION

The climate in Death Valley during summer months is one of the hottest and most arid in the world. The lowest land-surface elevation in the Western Hemisphere is in Death Valley, and much of the valley floor and areas of extreme temperature occur at elevations below mean sea level. Despite this harsh climate, numerous plant and animal species survive within Death Valley. Many of these plant and animal species are unique to the area, and depend on habitat provided by spring- and ground-water discharge.

Death Valley is a major natural discharge area of the Death Valley regional ground-water flow system (DVRFS), a regionally extensive closed hydrologic basin in southern Nevada and eastern California. The flow system, as delineated by Harrill and others (1988), encompasses an area of about 15,800 mi^2 (fig. 1). Ground-water discharge in Death Valley occurs at a series of springs and seeps along the east side of the valley and on the valley floor, as regional subsurface underflow, and within relatively large areas of the valley floor by evaporative discharge. Evaporative discharge occurs as vapor flux through bare soil, transpiration from phreatophytic vegetation, and evaporation from open-water surfaces. For the purposes of this report, the combined processes of evaporative discharge is referred to as evapotranspiration (ET).

Individual components of the ground-water budget in Death Valley are not accurately known and are difficult to quantify. Spring discharge often is poorly channeled and difficult to directly measure, especially in densely vegetated areas. Ground-water data typically are too sparse to accurately estimate regional subsurface flow between basins. Ground-water discharge by ET from Death Valley previously has not been estimated with collection of direct field measurements and observations. However, ET from selected areas of Death Valley has been estimated using indirect techniques, such as collecting pan ET rates and applying coefficients (Hunt and others, 1966) and by extrapolating ET rates determined for similar vegetation types in other areas of the southwestern United States (D'Agnese and others, 1997; Prudic and others, 1995).

The U.S. Geological Survey (USGS), in cooperation with the National Park Service (NPS) and Inyo County, California, from 1997 through 2001, estimated ground-water discharge from Death Valley by ET using direct field measurements, observations, and satellite-imagery data. This study applied techniques developed and refined during numerous studies of ET in Nevada and California, such as Walker and Eakin (1963), Duell (1990), Nichols (1991), Carman (1993), Nichols and others (1997), Laczniak and others (1999), Berger and others (2001), and Reiner and others (2002). More accurate estimates of ground-water discharge by ET will improve overall understanding of the DVRFS, provide information to develop a water budget for the basin, and help NPS managers evaluate the effects of future ground-water withdrawals within the DVRFS on the natural resources of Death Valley.

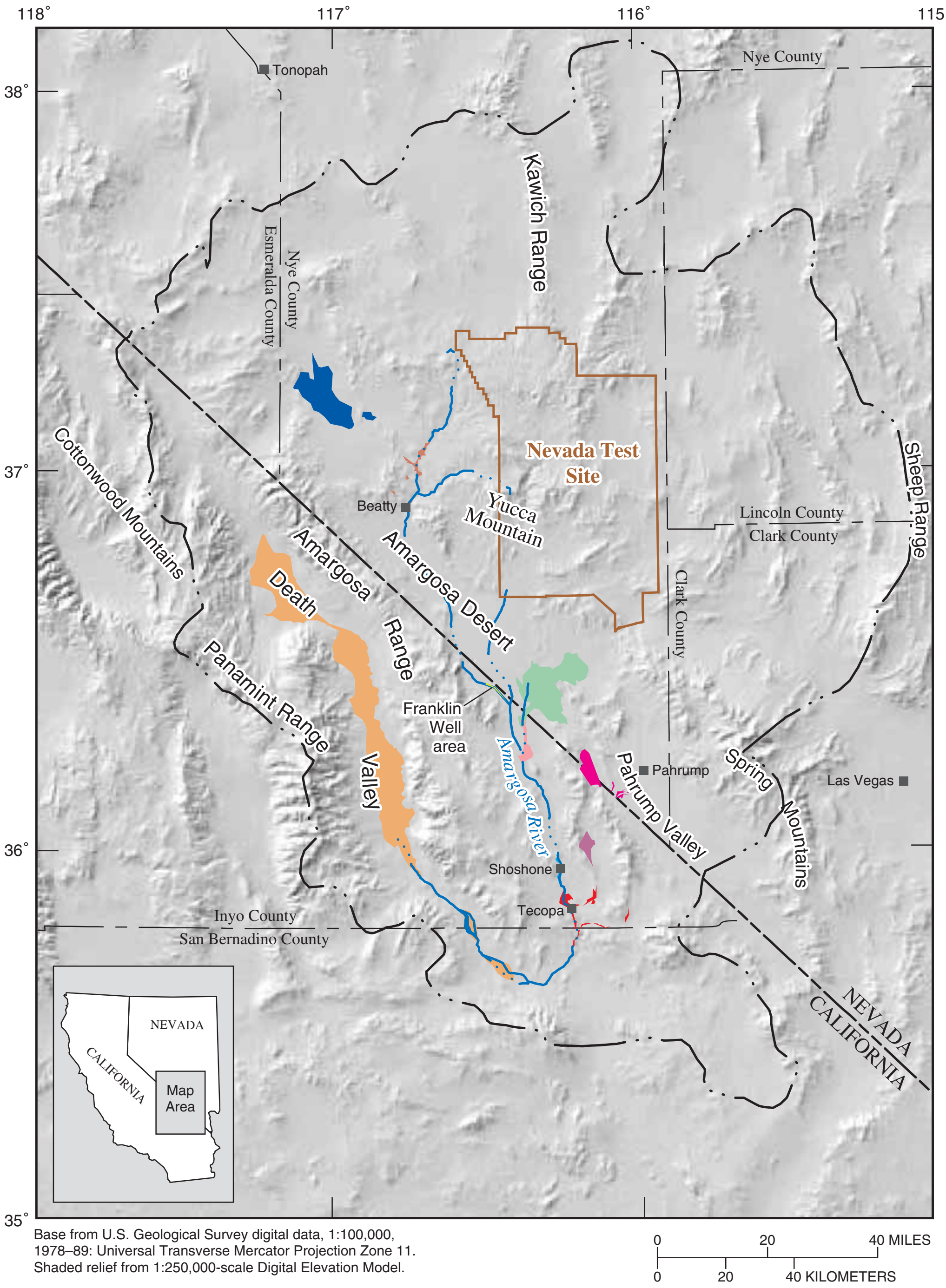
Purpose and Scope

The purpose of this report is to document results of a study to estimate evaporative ground-water discharge from Death Valley. The main focus of the study was the valley floor where shallow ground water either sustains phreatophytic plant communities or evaporates through bare soils. Localized areas of ET near a series of major springs along the eastern margin of Death Valley were not addressed in this study.

Analyses of satellite-imagery data and results from the National Wetlands Inventory (NWI; Cowardin and LaRoe, 1979) were applied to delineate the valley floor into areas of similar vegetation and soil types. ET rates were computed using micrometeorological data collected from instrumented sites within representative areas of similar vegetation and soil types. Finally, delineated areas and associated ET rates were used to estimate annual evaporative ground-water discharge from Death Valley.

Previous Investigations

Mendenhall (1909) is one of the earliest publications on water resources and hydrogeology in the Death Valley region. Subsequent publications addressing water resources and hydrogeology include Thompson (1929), Winograd (1962, 1971), Hunt and others (1966), Winograd and Thordarson (1975), Bedinger and others (1989), Prudic and others (1995), and Steinkampf and Werrell (2001). Studies addressing evapotranspiration within the region include Czarnicki (1990), Duell (1990), Nichols and others (1997), Laczniak and others (1999), Laczniak and others (2001), and Reiner and others (2002).



Base from U.S. Geological Survey digital data, 1:100,000,
1978–89: Universal Transverse Mercator Projection Zone 11.
Shaded relief from 1:250,000-scale Digital Elevation Model.

EXPLANATION

Ground-Water Discharge Area

- ■ Ash Meadows
- ■ Chicago Valley
- ■ Franklin Lake
- ■ Franklin Well area
- ■ Oasis Valley
- ■ Sarcobatus Flat
- ■ Shoshone area
- ■ Stewart Valley
- ■ Tecopa/California Valley area
- ■ Death Valley (not evaluated as part of study)

—— · · —— **Death Valley Regional Flow System boundary**—From Harrill and others (1988)

Figure 1. Death Valley ground-water flow system, California and Nevada.

Acknowledgments

The NPS-Water Resources Division and Inyo County, California, contributed cooperative funding for this study. The authors express their appreciation to Richard Anderson, Mel Essington, Doug Threloft, and other NPS employees at Death Valley National Park who provided assistance with permits needed to access environmentally sensitive areas within the park, logistics and site support for collecting field data and observations, and insight and information about natural resources in Death Valley. The authors also extend their appreciation to William D. Nichols formerly of the U.S. Geological Survey for his time and valuable technical assistance in this work.

Description and Setting

Death Valley National Park is in southeastern California and adjacent parts of southern Nevada (fig. 2). The park includes all of Death Valley, adjacent mountainous areas, and several other smaller neighboring valleys.

Death Valley is within the southern Great Basin region of the Basin and Range physiographic province of the western United States. Topography in the region is characterized by numerous linear, north-south trending, elongate valleys that are separated by fault-block mountain ranges. The topography is the result of an extensive period of tectonic activity and crustal extension that is still active. The valleys are filled with relatively thick sequences of Cenozoic alluvium eroded from adjacent mountain ranges and evaporite deposits. Valleys are characterized by alluvial fans sloping to relatively flat floors; elevation of individual valley floors ranges from 282 ft below sea level to about 5,000 ft above sea level. Basement rocks beneath the valleys consist of thick sequences of Proterozoic and Paleozoic carbonate, clastic, and volcanic rocks. Blocks of basement rock uplifted along vertically displaced faults form mountain ranges adjacent to the valleys. Higher peaks in these mountain ranges crest at 8,000 to greater than 11,000 ft above sea level (Hunt and others, 1966).

Death Valley is a 156-mile long structural trough that generally trends north-south to northwest-southeast and is bounded by the Panamint Range and Cottonwood Mountains to the west, the Amargosa Range mountains to the east (fig. 1), and the Owlshead Mountains to the south (fig. 2).

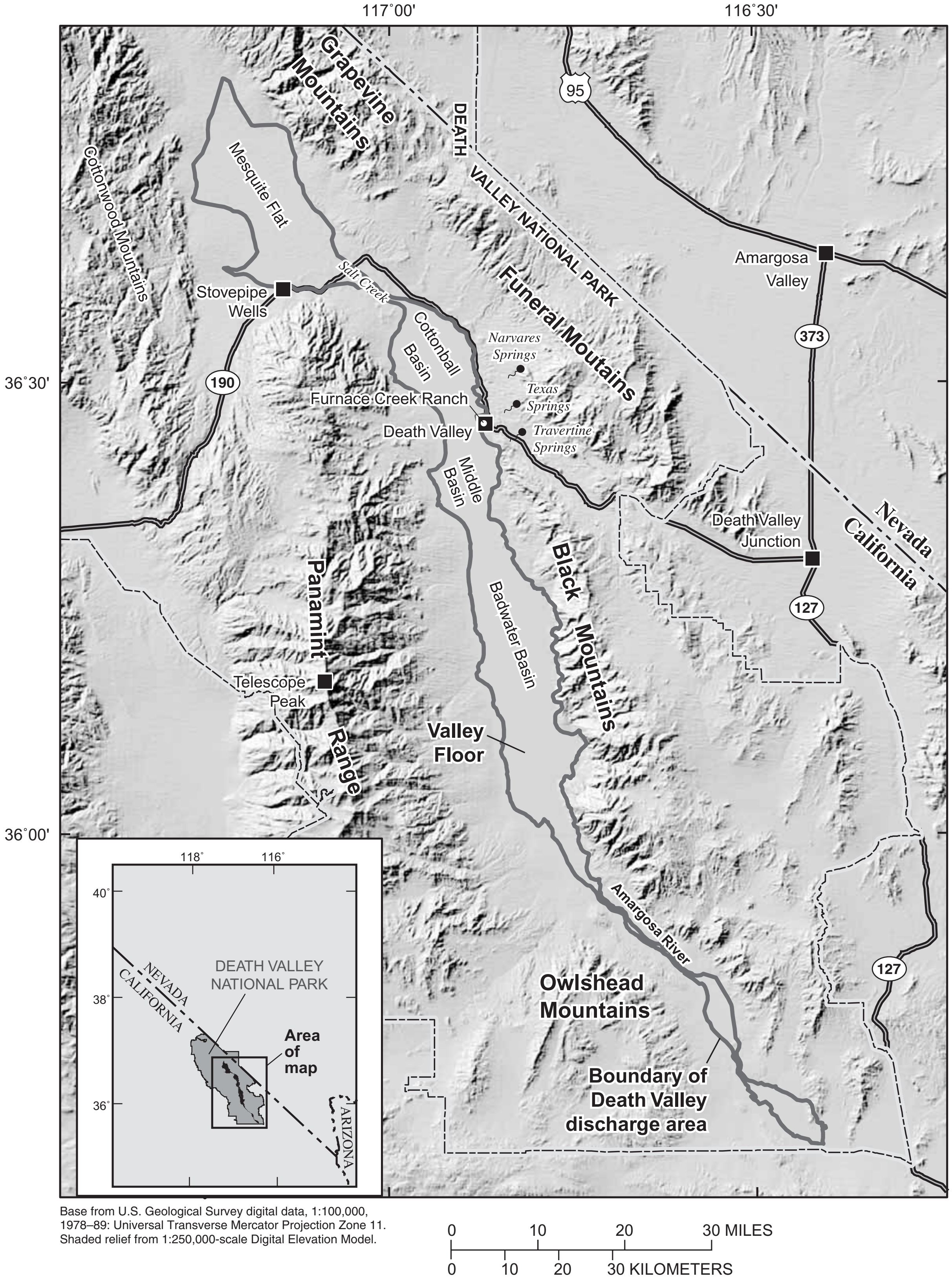
The floor of Death Valley consists of three areas (fig. 2): Mesquite Flat, the saltpan, and an area south of the saltpan along the Amargosa River channel. The saltpan is a saline playa-lake flat characterized by areas of salt-encrusted deposits and saliniferous soils. The saltpan is subdivided into areas from north to south named Cottonball Basin, Middle Basin, and Badwater Basin (Hunt and others, 1966). Most of the floor of Death Valley lies below sea level; the lowest elevation in the Western Hemisphere (282 ft below sea level) is in Badwater Basin in the central part of Death Valley. Telescope Peak in the Panamint Range is the highest elevation (11,049 ft above sea level) near the Death Valley National Park. Mesquite Flat is an area northwest of the saltpan characterized by areas of phreatophytic vegetation supported by shallow ground water.

Climate

Death Valley is one of the hottest and most arid places in the Western Hemisphere with temperatures commonly exceeding 120°F during summer months. The greatest temperature ever recorded by the National Weather Service (NWS) in the United States was 134°F (Desert Research Institute, 2003); which occurred in Death Valley on July 10, 1913. Soil-surface temperatures as high as 150°F were recorded during this study in Death Valley. Precipitation in the Death Valley area is erratic varying with time, location, and altitude. The mean annual rainfall at Furnace Creek Ranch is 2.26 in. (NWS station ID 042319, 1961–2001). In higher parts of adjacent mountain ranges, mean annual precipitation has exceeded 10 in. Precipitation tends to be greatest in winter and least in summer, generally increases with altitude, and tends to vary temporally with wet and dry cycles such as El Niño and La Niña. Relative humidity can be less than 5 percent during summer months. Winds in Death Valley frequently are gusty and typically blow from the southeast during the afternoons and from the northwest in the early mornings.

Vegetation

Large areas of Death Valley are covered by Lower Sonoran zone vegetation and bare soils (Hunt, 1966). Lower Sonoran zone vegetation primarily consists of creosotebush shrubs (*Larrea tridentate*), although other xerophytes such as desert holly (*Atriplex hymenelytra*), cattle spinach (*Atriplex polycarpa*), burroweed (*Franseria dumosa*), and incienso (*Encelia farinose*)



Base from U.S. Geological Survey digital data, 1:100,000, 1978–89: Universal Transverse Mercator Projection Zone 11. Shaded relief from 1:250,000-scale Digital Elevation Model.

Figure 2. Location of valley floor and other major physiographic features of Death Valley.

commonly occur. Density of the xerophytes ranges from just a few per acre to a maximum of several hundred per acre (Hunt and others, 1966). Bare soils occur in saltpan and playa areas where vegetation does not grow because of excessive salinity or in areas of well-developed desert pavement such as on parts of alluvial fans along valley margins. Limited areas of phreatophytic vegetation occur within spring-discharge areas and other areas of shallow ground water where the water is not too saline. Types of phreatophytic vegetation include mesquite trees (*Prosopis*), pickleweed (*Allenrolfea*), arrowweed (*Pluchea sericea*), salt and bunch grasses (*Atriplex canescens*, *Nassella pulchra*), assorted marsh grasses, and other desert shrubs. Although limited in total acreage, these areas provide important habitat for numerous wildlife species. Higher altitude areas of Death Valley National Park, such as the Panamint Range and the Grapevine and Cottonwood Mountains (fig. 2), support upper Sonoran and Arctic/Alpine vegetation zones.

Hydrology

Death Valley is a terminal discharge area for regional ground-water flow; as a result, ground water occurs at relatively shallow depths in many parts of the valley. In addition to regional interbasin ground-water flow, water enters Death Valley from precipitation that infiltrates in bordering mountains and valley margin areas, intermittent surface-water runoff along ephemeral channels into the valley during infrequent rainstorms, and water discharged at valley margin springs and seeps that infiltrates and flows to the valley floor. Springs and seeps in Death Valley occur where water is forced to the surface by low-permeability structural deposits (such as near Salt Creek; fig. 2) or where water ponds in sand and gravel deposits adjacent to low-permeability silt deposits (such as marginal areas along the saltpan). Regional ground water also discharges at a series of springs above the eastern margin of the valley and tends to occur along high-angle faults. Ground water beneath the saltpan is hypersaline; specific-conductance field measurements of shallow ground water exceed 200,000 µS/cm. Specific conductance of ground water in other areas can vary, exceeding 20,000 µS/cm near Salt Creek.

Water discharged by springs and seeps is either diverted to supply water for park operations, is used by riparian vegetation, or tends to rapidly infiltrate or evaporate. Discharge at most of the springs tends to diffuse and does not follow an established channel. Springs above the eastern margin of the valley typically discharge greater than 0.5 ft^3/s (Steinkampf and Werrell, 2001). Springs in other areas typically discharge less than 6.0×10^{-3} ft^3/s. The Amargosa River (fig. 1) is an intermittent stream that drains about 5,546 mi^2 to the east of Death Valley and terminates at the southern end of the Death Valley saltpan (Badwater Basin; fig. 2). Intermittent flow occurs in the lower part of the Amargosa River after some rainfall events causing surface water to occasionally be discharged onto the Death Valley saltpan. Salt Creek drains Mesquite Flat and mountainous areas in the northern part of Death Valley, north of the saltpan. The lower reach of Salt Creek flows during most of the year, typically discharging about 1.0 ft^3/s.

EVAPOTRANSPIRATION UNITS

ET units are areas of similar vegetation density, soil type, and moisture content. ET rates have been shown to correlate well with these vegetation and soil characteristics (Ustin, 1992; Laczniak and others, 1999; Nichols, 2001; and Reiner and others, 2002). Five ET units were delineated within the discharge area to minimize the variability of evapotranspiration rates within an area of interest and to facilitate the estimation of total evaporative discharge from the floor of Death Valley. Evaporative discharge from each ET unit was calculated as the product of the unit's area and average evapotranspiration rate. Total evaporative discharge from the valley floor was computed by summing the evaporative discharge computed for each of the units.

Three ET units dominated by phreatophytic vegetation were mapped using satellite (Thematic Mapper) imagery. These units were mapped at a resolution of about 100 x 100 ft—the pixel size of Thematic Mapper (TM) imagery. The average surface reflectance (percent reflectance) for the six spectral bands within the visible to infrared range [0.4–2.4 µm (micrometer)] of a TM image was estimated by correcting the raw spectral data for scene illumination, atmospheric conditions, viewing geometry, and instrument response characteristics (Lillesand and Kiefer, 1987).

The procedure used to map vegetation-dominated ET units was TM bands 3 (red wavelength) and 4 (near infrared wavelength). The use of selected bands to map vegetation is commonly referred to as a vegetation index (Elvidge and Zhikang, 1995). The specific index used for this study is known as the modified soil-adjusted vegetation index (MSAVI; Qi and others, 1994). Soil-adjusted indices were developed to minimize soil influences within the measured spectra and are more sensitive to spatial changes in vegetation (Heute, 1988).

Vegetation-dominated ET units were delineated using multiple MSAVI values computed from six TM scenes imaged over 3 years (1994–96). The time series constructed from these six MSAVI values is referred to as a temporal signature (fig. 3). These temporal signatures are inclusive of vegetation changes caused by seasonal and longer-term climatic variations. This approach differs from that used by Laczniak and others (1999, 2001) and Reiner and others (2002) in other major discharge areas within the DVRFS. Their approach delineated vegetation and soil covers using spectral signatures derived from the six TM bands in the visible and near-infrared regions of the electromagnetic spectrum. A total of 275 temporal signatures were defined on the basis of changes in the temporal MSAVI values. Nineteen of the 275 signatures were determined by analyzing MSAVI values for vegetation near sites equipped with instrumentation to measure ET rates. The remaining 256 signatures were computed using an algorithm (ERDAS®, Inc., 1997) that determines a given number of unique signatures from the range of MSAVI values within an image (specific time) and throughout the images (entire time period). One signature was assigned to each pixel (fig. 3) using a matching algorithm. This procedure was applied only to that part of the imagery within the area of probable ground-water discharge as delineated by Harrill and others (1988).

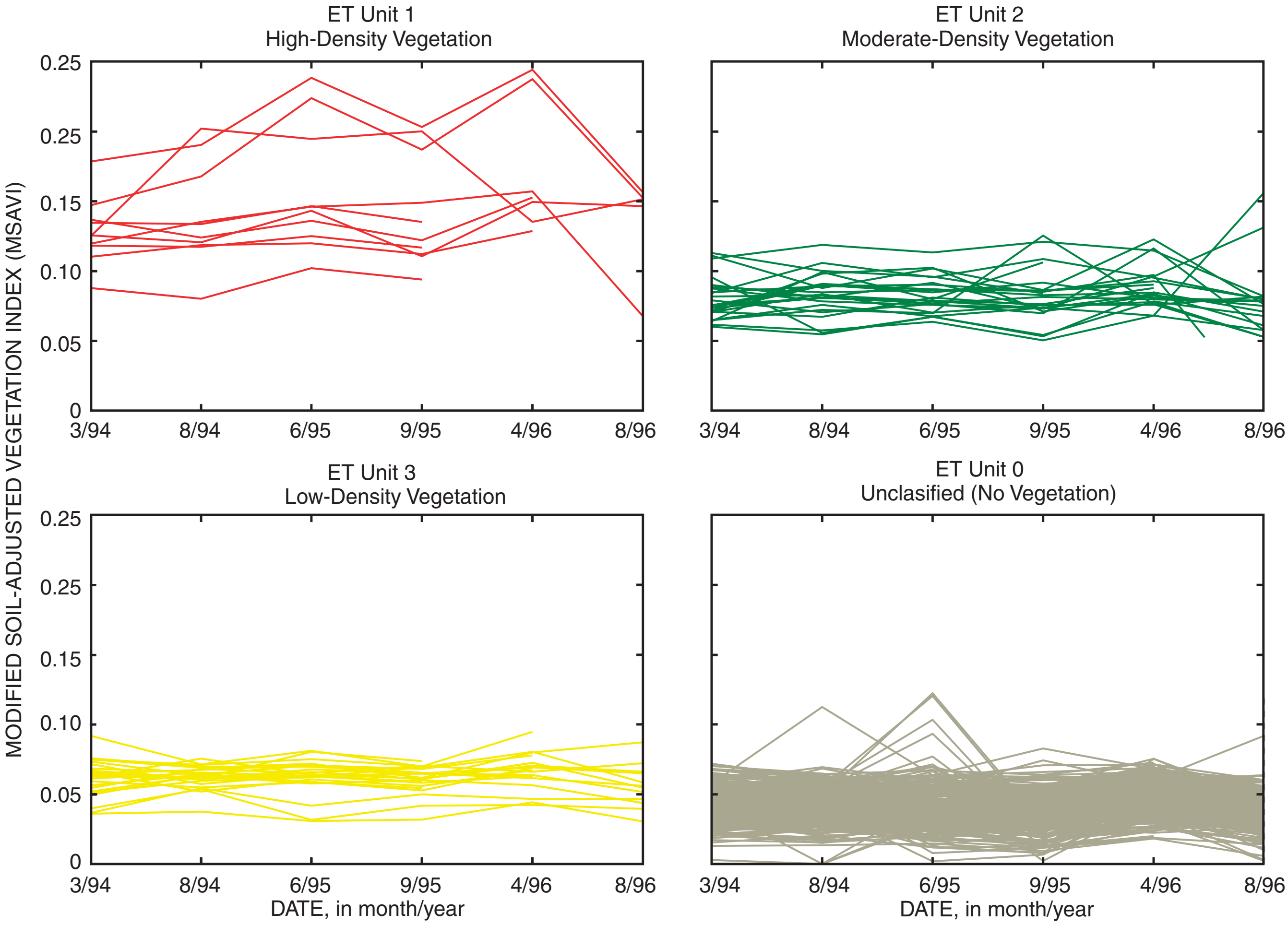


Figure 3. Temporal modified soil-adjusted vegetation indices (MSAVI) clusters of signatures used to delineate vegetation in Death Valley.

Vegetation-dominated ET units were defined by grouping similar temporal signatures into three clusters of similar vegetation density. Individually and collectively the three resulting ET units (low-, moderate-, and high-density vegetation; fig. 4) have limited areal extent constituting only about 13,100 acres or about 12 percent of the land cover within the ground-water discharge area (table 1).

Two other ET units were mapped to represent soil-dominated land covers within the discharge area. These units were delineated on the basis of field reconnaissance information and wetland-unit extents reported in the NWI (U.S. Fish and Wildlife Service, 1996). The two soil-dominated ET units are bare and salt encrusted (fig. 4, table 1). Areas of low-density vegetation identified within these soil-dominated units were checked and validated by field visitation. Areas falsely identified through remote sensing were eliminated and assigned to the appropriate soil unit. Together these two units account for about 97,000 acres or about 88 percent of the land cover within the ground-water discharge area.

EVAPOTRANSPIRATION RATES

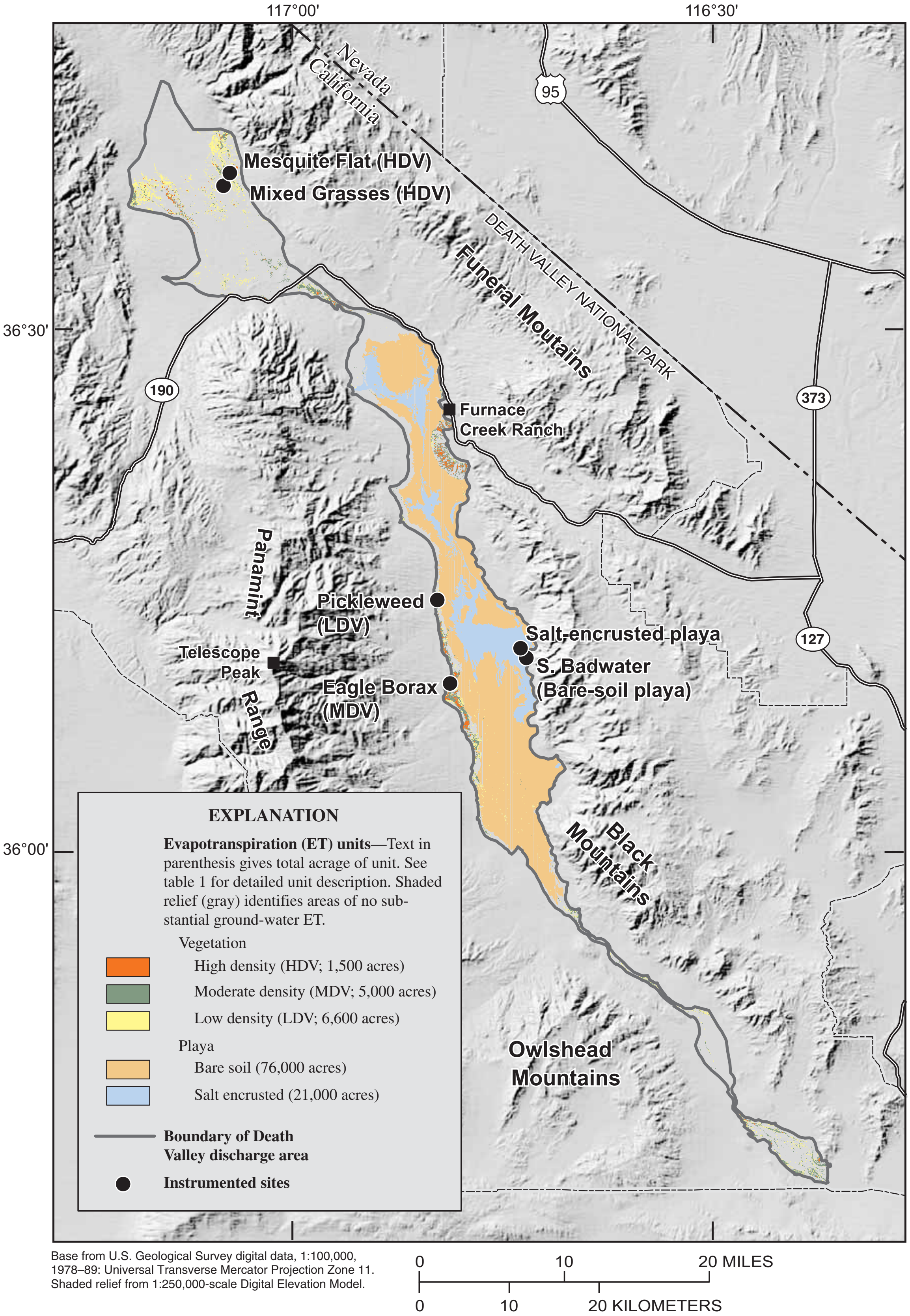
ET is a process by which water, at or near the earth's surface, evaporates or is transpired by vegetation and is thereby transferred to the atmosphere. As ET occurs, water changes state from a liquid to a gas by consuming energy from solar and terrestrial radiation, turbulent kinetic energy, and from heat stored in soil and atmosphere. The relation between changing energy consumption and corresponding water loss is the basis for energy-budget methods used to estimate ET rates. Energy-budget methods were applied in this study using micrometeorological and soil data collected from representative vegetation groups in Death Valley to estimate daily and annual ET rates.

Table 1. Evapotranspiration units determined from temporal analysis of modified soil-adjusted vegetation indices (MSAVI), Death Valley, California

[Symbol: --, not applicable. Abbreviations: ET, evapotranspiration; ft, feet]

ET-unit identifier	ET-unit number	ET-unit area, in acres	General description of ET unit[1]
UCL	0	--	Unclassified (UCL) area with no substantial ET from any ground-water sources; water table typically greater than 20 ft below land surface; soil very dry.
HDV	1	1,522	Area of high-density vegetation (HDV), primarily marsh and meadow grasses, and mesquites; perennially flooded; water table typically ranges from near land surface to about 20 ft below land surface; soil wet to dry.
MDV	2	5,019	Area dominated by moderate-density vegetation (MDV), primarily salt and bunch grasses, arrowweed, mesquite, minor pickleweed; water table typically ranges from about 2 to 20 ft below land surface; soil moist to dry.
LDV	3	6,625	Area dominated by low-density vegetation (LDV), primarily salt grass, pickleweed, and shrub mesquite; water table typically ranges from about 5 to 20 ft below land surface; soil damp to dry.
BSP	5	75,922	Area of playa dominated by bare-soil playa (BSP), primarily silt; some salt encrustation; water table typically ranges from a near land surface to about 10 ft below land surface; water table declines during summer months; occasionally flooded; soil damp to dry.
SEP	6	21,287	Area of playa dominated by salt-encrusted playa (SEP); occasionally flooded, water table typically near land surface to about 5 ft below land surface; salt wet to dry.

[1] Vegetation cover descriptor: low density is from greater than 5 to less than 15 percent; moderate density is 15–50 percent; and high density is greater than 50 percent. Soil-moisture descriptor presented in relative terms. Sources for depth-to-water information are U.S. Geological Survey National Water Information System at web site <**http://waterdata.usgs.gov/nwis**> (last retrieved August 2003), and depth-to-water measurements made during the study.



Base from U.S. Geological Survey digital data, 1:100,000,
1978–89: Universal Transverse Mercator Projection Zone 11.
Shaded relief from 1:250,000-scale Digital Elevation Model.

Figure 4. Distribution of evapotranspiration units and location of instrumented sites in Death Valley.

A number of methods have been developed to estimate ET using the relation between water loss and energy consumption. In this study the Bowen ratio method (Bowen, 1926) was applied to estimate ET rates in Death Valley because of its robustness, reliability, and accuracy. At one site ET rates also were estimated using the eddy correlation method (Stull, 1988) to compare with the Bowen ratio method as a check to see if similar results could be achieved with two different methodologies.

Site Selection and Instrumentation

Sites were selected for data collection based on field reconnaissance and preliminary ET-unit classification. Instrumented platforms (ET sites) were installed at six locations (fig. 4, table 2): salt-playa site (extensive salt encrustation), bare-soil playa site (silt and salt encrustation), pickleweed site (pickleweed plants, low-density vegetation), Eagle-Borax site (arrowweed plants and salt grass, moderate-density vegetation), Mesquite Flat site (mesquite trees, high-density vegetation), and Mesquite Flat mixed grass site (mixed meadow grasses, high-density vegetation). An ET site was not established for the open-water unit because its area (only 2 acres) was insignificant in comparison to other ET units. Sites were not installed in locations outside the valley floor (fig. 2). For purposes of this study, the valley floor is considered the principal discharge area for Death Valley. A photograph of each ET site is shown in figure 5. Data on site coordinates and measurement period-of-record are listed in table 2.

The distance between instrument sensors and the upwind edge (upwind fetch) of the environment under study also was an important parameter for site selection. A proper fetch ensures that sampled heat and vapor fluxes are representative of the environment of interest. To achieve a proper fetch, sites were selected where the distance to the edge of the environment was at least 100 times the height of the highest air temperature-humidity sensor (about 800 ft; Campbell, 1977). All ET sites were equipped with instruments to collect micrometeorological data for energy-budget calculations using the Bowen ratio method. These instruments could either directly measure energy-budget components or be used to compute these components from direct measurements. A schematic of instrumentation used to collect data for the Bowen ratio and eddy correlation methods is shown in figure 6.

Table 2. Location, depth of piezometer, and period of data collection for instrumented sites used to collect micrometeorologic data, Death Valley, California, 1997–2001

[Abbreviations: ET, evapotranspiration. ET units description: SEP, salt-encrusted playa; BSP, bare-soil playa; LDV, low-density vegetation, MDV, moderate-density vegetation; HDV, high-density vegetation. See table 1 for description of ET units]

ET-site name	ET unit	Latitude	Longitude	Depth of piezometer, in feet	Period of data collection
Salt playa[1]	SEP	36°13′40″	116°47′07″	13.8/3.9	06/98 – 07/01
Bare-soil playa[1]	BSP	36°12′52″	116°46′29″	10.8/5.6	08/97 – 12/99
Pickleweed	LDV	36°17′12″	116°53′12″	14.0	03/98 – 08/00
Eagle Borax	MDV	36°11′46″	116°52′04″	9.3	01/00 – 09/01
Mesquite Flat	HDV	36°44′45″	117°08′11″	14.2	01/99 – 09/01
Mesquite Flat mixed grasses	HDV	36°44′19″	117°08′44″	9.2	03/00 – 09/01

[1] Site has two piezometers for water-level measurements at multiple depths below land surface.

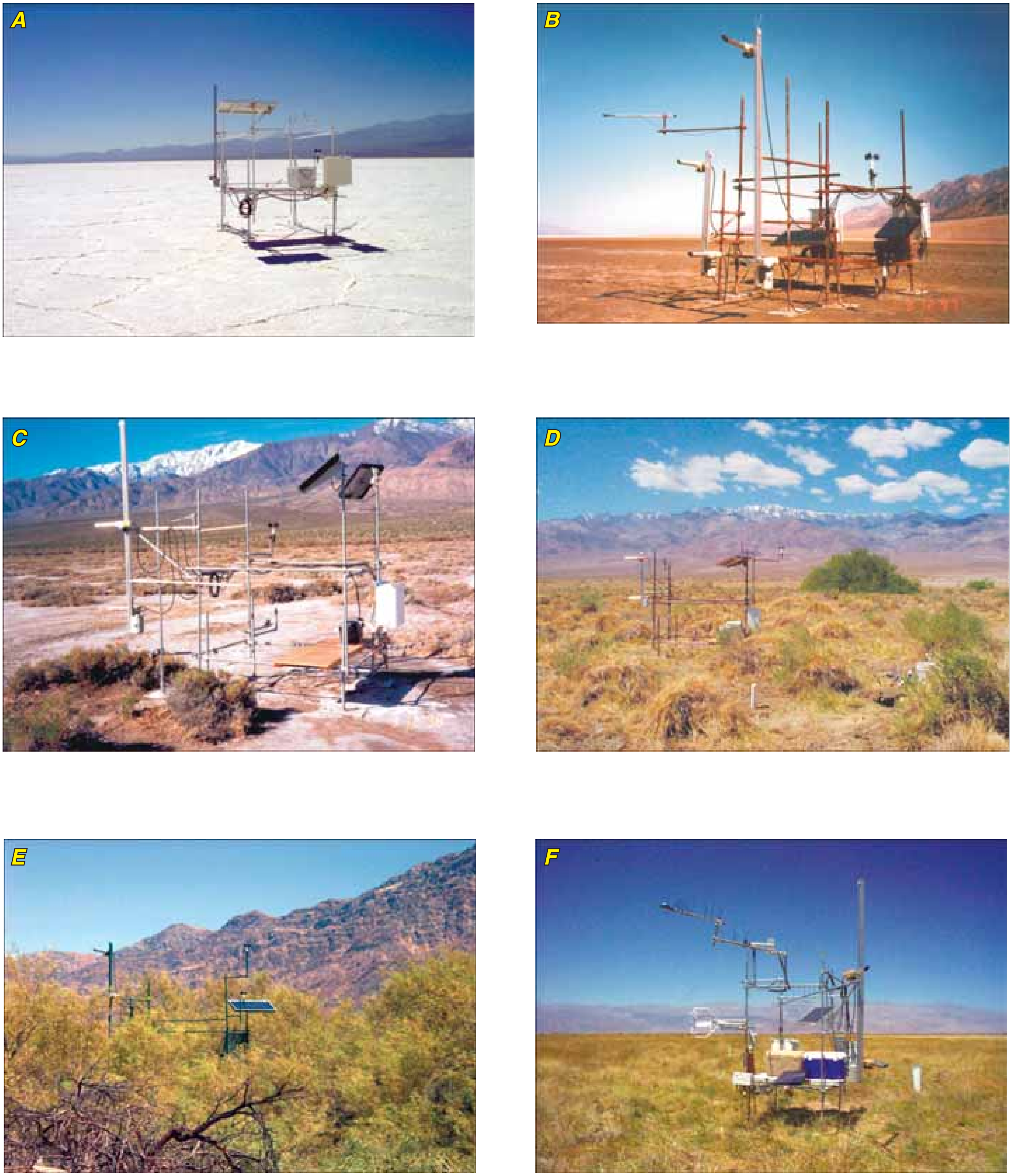


Figure 5. Evapotranspiration sites at (*A*) salt-encrusted playa, (*B*) bare-soil playa, (*C*) pickleweed, (*D*) Eagle Borax, (*E*) Mesquite Flat, and (*F*) Mesquite Flat mixed grasses, Death Valley, California, August 1998–October 2001.

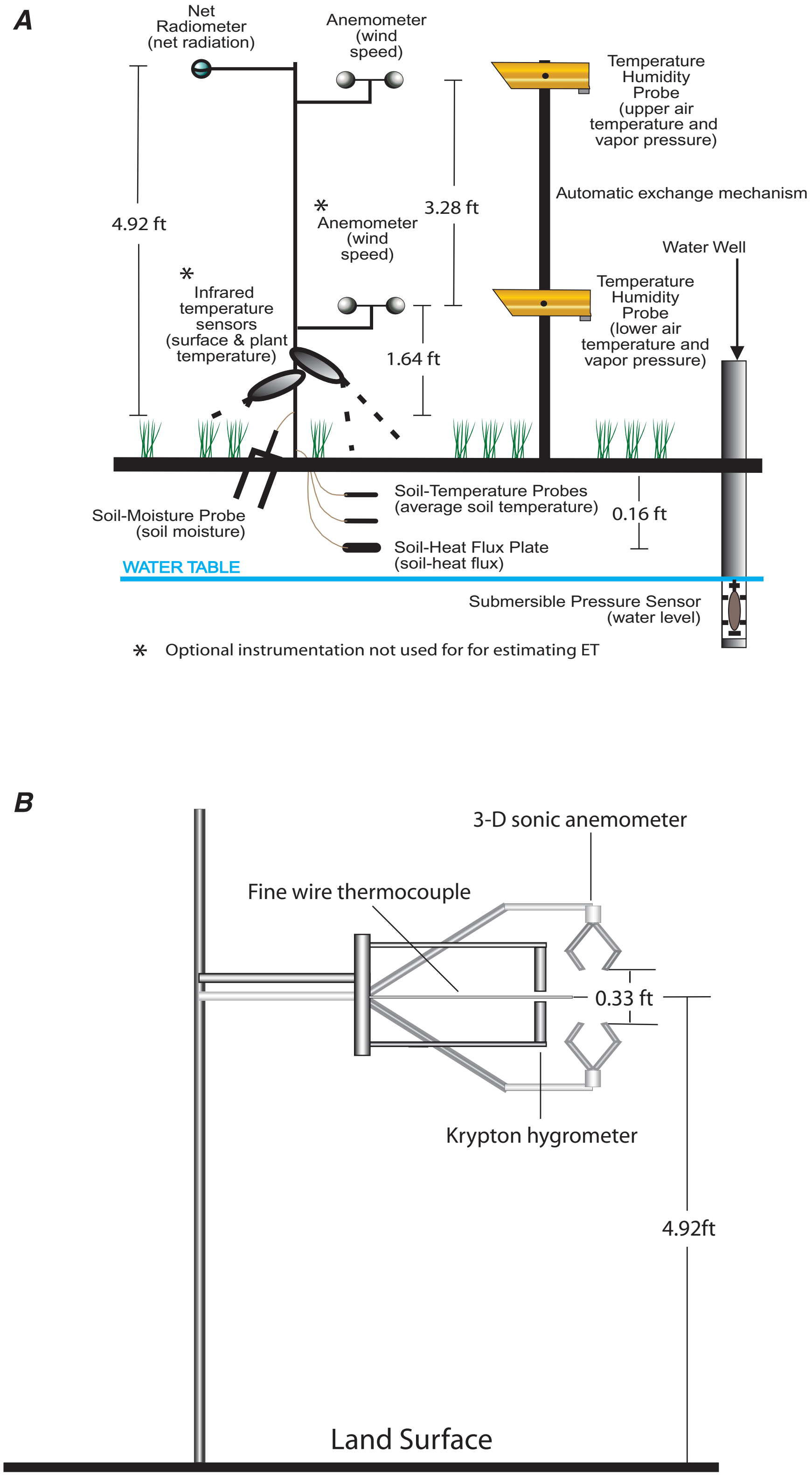


Figure 6. Schematic of typical micrometeorological data-collection site for computation of evapotranspitation by (*A*) Bowen ratio method and (*B*) eddy correlation method, Death Valley, California, 1997–2001.

Site instruments included:

- A net radiometer to measure incoming and reflected short- and long-wave radiation,
- Two air temperature-humidity probes (THPs) at reference heights of 4.92 and 8.2 ft above average plant canopy height,
- An anemometer to measure wind speed at the same height as upper THP,
- Two soil heat-flux (SHF) plates to measure the rate of change of heat stored in the soil or water profile at 0.16 ft below land surface,
- Subsurface soil-temperature probes (evenly spaced between land surface and SHF),
- A soil-moisture probe angled between land surface and 0.16 ft below land surface,
- A submersible pressure sensor to continually measure water levels in a shallow piezometer, and
- A volumetric precipitation gage.

The THPs were calibrated by the manufacturer to specifically operate within the range of extremely low relative humidity and high air-temperature values common to Death Valley. An automatic exchange mechanism was used to swap the THPs between reference heights every 10 minutes to remove any air temperature and relative humidity bias that exists between the two probes (Fritschen and Simpson, 1989; Fritschen and Fritschen, 1993). Four of the six sites also were equipped with two infrared temperature sensors to measure soil-surface and plant-canopy temperatures and a second anemometer at the height of the lower THP (fig. 6*A*).

The Mesquite Flat mixed-grasses site was additionally equipped with instruments (fig. 6*B*) to collect data needed to compute sensible- and latent-heat flux using the eddy correlation method:

- A krypton hygrometer to measure water-vapor density and
- A three-dimensional sonic anemometer to measure vertical wind speed and air temperature.

Energy-Budget Methods

Bowen Ratio Method

The exchange of energy at the earth's surface during the ET process can be described as a balance between incoming and outgoing energy fluxes (fig. 7). The balance for an arid environment such as Death Valley can be mathematically expressed using an energy-budget equation of the form

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

where R_n is net radiation,
H is sensible-heat flux (energy per second per area),
G is soil-heat flux (energy per second per area),
λE is latent-heat flux (energy per second per area),
λ is latent heat of vaporization for water (energy per mass), and
E is rate of water-vapor flux (mass per time per area).

Net radiation is the principal source of energy at the surface of the earth and is the algebraic sum of incoming and outgoing long- and short-wave radiation. Soil-heat flux is the energy stored in the soil near the earth's surface. Net radiation and soil-heat flux can be directly computed using field data. The difference between net radiation and soil-heat flux is the energy available for sensible- and latent-heat flux.

Sensible-heat flux is the energy used to heat air at the earth's surface and is proportional to the product of the temperature gradient and the turbulent-transfer coefficient for heat. This flux can be expressed as

$$H = \rho_a C_p k_h((T_l - T_u)/(z_l - z_u)) \qquad (2)$$

where ρ_a is density of air (mass per volume),
C_p is specific heat of air at a constant pressure (energy per mass per temperature),
k_h is turbulent transfer coefficient of sensible heat (area per time),
$T_{l,\,u}$ is lower (*l*) or upper (*u*) reference point temperature of air, and
$z_{l,\,u}$ is lower (*l*) or upper (*u*) height at which reference point temperature of air is measured (length).

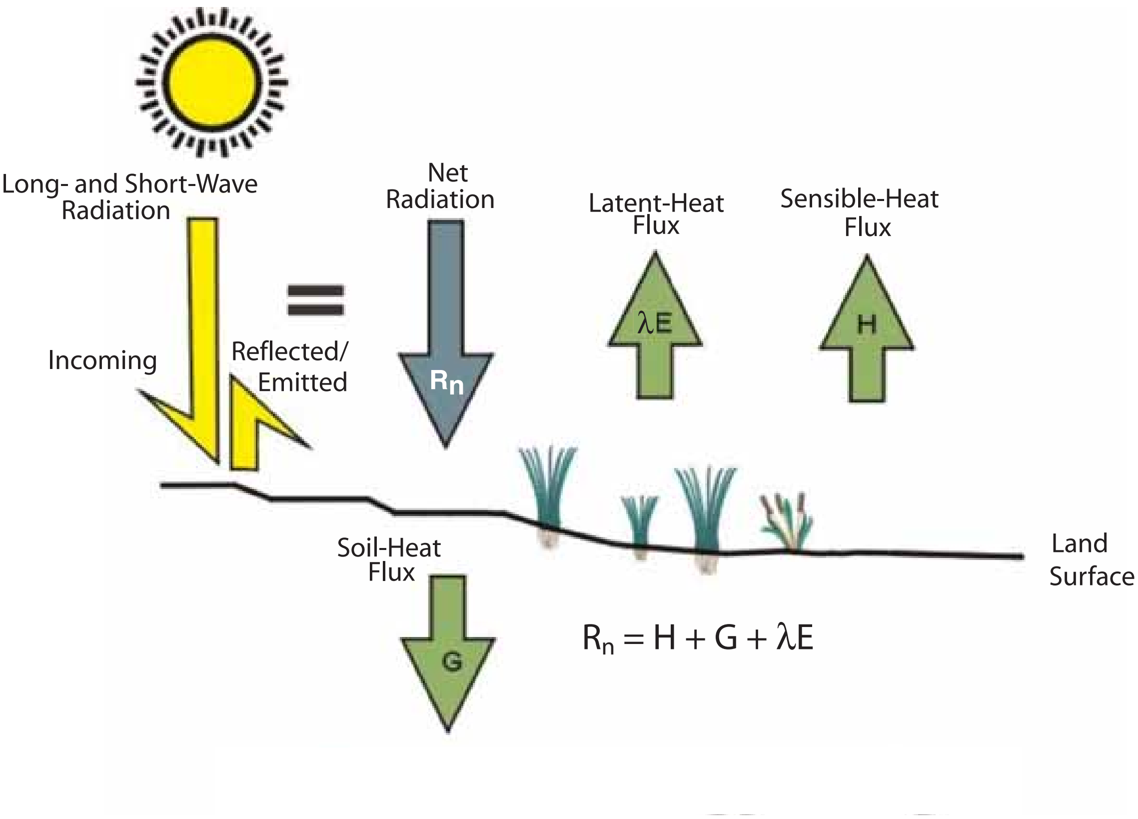


Figure 7. Schematic showing components of the surface-energy budget.

Latent-heat flux is the energy used for ET. In a flux-gradient format, it is proportional to the product of the vapor-pressure gradient and the turbulent-transfer coefficient of vapor and can be expressed as

$$\lambda E = ((\lambda \rho_a \varepsilon k_v / P)(e_l - e_u))/(z_l - z_u) \tag{3}$$

where ε is ratio of molecular weight of water vapor to dry air (dimensionless),

k_v is turbulent transfer coefficient of vapor (area per time),

P is ambient air (barometric) pressure (force per area),

$e_{l,u}$ is lower (l) or upper (u) reference point vapor pressure (force per area), and

$z_{l,u}$ is lower (l) or upper (u) height at which reference point vapor pressure is measured (length).

Equations 2 and 3 cannot be directly solved because the turbulent-transfer coefficients of heat and vapor are not known. Bowen (1926) developed an indirect method for solving the energy-budget equation by assuming the turbulent-transfer coefficients were equal and expressing the ratio of sensible-heat flux to latent-heat flux as

$$H/(\lambda E) = \gamma\left[(T_l - T_u)/(e_l - e_u)\right] \tag{4}$$

where γ is the ratio $(PC_p)/(\lambda\varepsilon)$ and referred to as the psychrometric constant. The psychrometric constant is a function of air pressure and temperature and is almost constant for a given altitude (Fritschen and Gay, 1979). The ratio of sensible-heat flux to latent-heat flux as expressed in equation 4 is referred to as the Bowen ratio (β). When the β is substituted into equation 1, latent-heat flux can be re-expressed as

$$\lambda E = (R_n - G)/(\beta + 1)\,. \tag{5}$$

ET is the mass flux of water into the atmosphere and can be calculated with latent-heat flux as

$$ET = \lambda E/(\lambda\rho_w) \qquad (6)$$

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

ρ_w is the density of water.

Eddy Correlation Method

Rapidly ascending and descending turbulent currents of air exchanging heat and water vapor between the land surface and the atmosphere are called eddies. The eddy correlation method determines H and λE by calculating a covariance between fluctuations in vertical wind speed, air temperature, and water-vapor density. Vertical wind-speed, air-temperature, and water-vapor density data are sampled at high frequencies and used to calculate H and λE. Unlike the Bowen ratio, H and λE can be determined independently of R_n or G. Using the eddy correlation method, H is proportional to the covariance between the vertical wind speed and instantaneous air temperature measured at a point and can be expressed as

$$H = \rho_a C_p \overline{w'T} \qquad (7)$$

where w' is the instantaneous deviation of vertical wind speed from the mean (length per time) and T is the instantaneous deviation of air temperature from the mean (degrees kelvin).

Using this same approach, λE is proportional to the covariance between the instantaneous vertical wind speed and water vapor density at a point and can be expressed as

$$\lambda E = \lambda \overline{w'\rho_v'} \qquad (8)$$

where ρ_v' is the deviation of water-vapor density from the mean (mass per volume). ET is calculated for the eddy correlation method by substitution of λE from equation 8 and into equation 6.

Micrometeorological Data

Micrometeorological data required for solving the energy budget by the Bowen ratio or eddy correlation methods were collected at each ET site for a period of 1 year or more. A minimum period of 1 year was required to evaluate and document seasonal fluctuations in ET rates and compute an annual ET value. Additional years of data were acquired to better assess annual changes in ET that may result from climatic variations, such as differences between dry and wet years. Micrometeorological data were collected for this study from August 1997 to October 2001 (table 2).

Data collected for the Bowen ratio calculations were sampled at either 10- or 30-second intervals. For eddy correlation calculations, the krypton hygrometer and the three-dimensional sonic anemometer both sampled data at a 0.1-second interval. Bowen ratio and eddy correlation data were collected and stored for final use as 20-minute averages that were then used to calculate 20-minute average ET rates. An example of micrometeorological data needed to compute the Bowen ratio is shown in figure 8 for a 5-day period at the Mesquite Flat mixed-grasses site.

Daily and Annual Evapotranspiration

Daily ET rates were determined by summing 20-minute average ET rates computed from measured micrometeorological data and calculated energy fluxes. This process includes (1) determining individual components of the energy budget (net radiation, latent-heat flux, sensible-heat flux, and soil-heat flux; fig. 9*A*) from measured micrometeorological data, (2) using equation 6 to determine 20-minute ET rates from 20-minute latent-heat flux, and (3) determining daily ET by summing 20-minute ET values for a 24-hour period (fig. 9*B*). Energy-budget fluxes typically follow a diurnal pattern, obtaining their maximum values during daylight hours when incoming solar radiation is at its peak. How energy is partitioned between these components is dependant on the site environment. For example, evaporation generally is the dominant process at sites with dense vegetation or moist soils. This environment typically causes latent-heat flux to be greater than sensible-heat flux. At sites with a relatively high percentage of exposed bare soil or dormant vegetation, heating of the land surface generally is the dominant process and this environment typically causes sensible- and soil-heat fluxes to exceed latent-heat flux.

Due to periodic equipment failures collected data were sometimes not usable for ET calculation. These data gaps ranged from 12 to 63 consecutive days and collectively up to 110 days during 1 year of data collection at the Mesquite Flat site. Daily ET values are

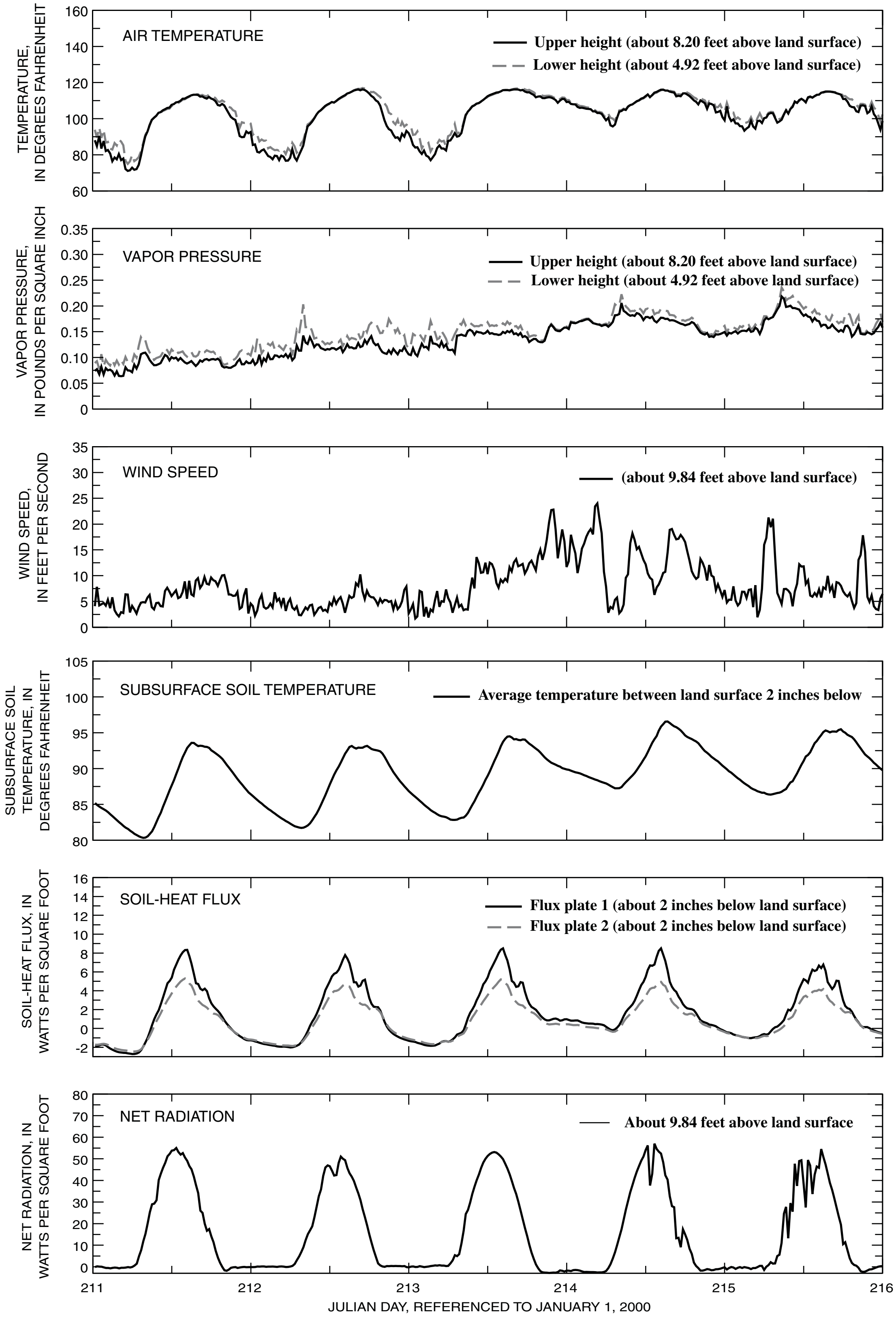


Figure 8. Twenty-minute averaged micrometeorological data collected from the Mesquite Flat mixed-grasses site, Death Valley, California, July 29–August 2, 2000.

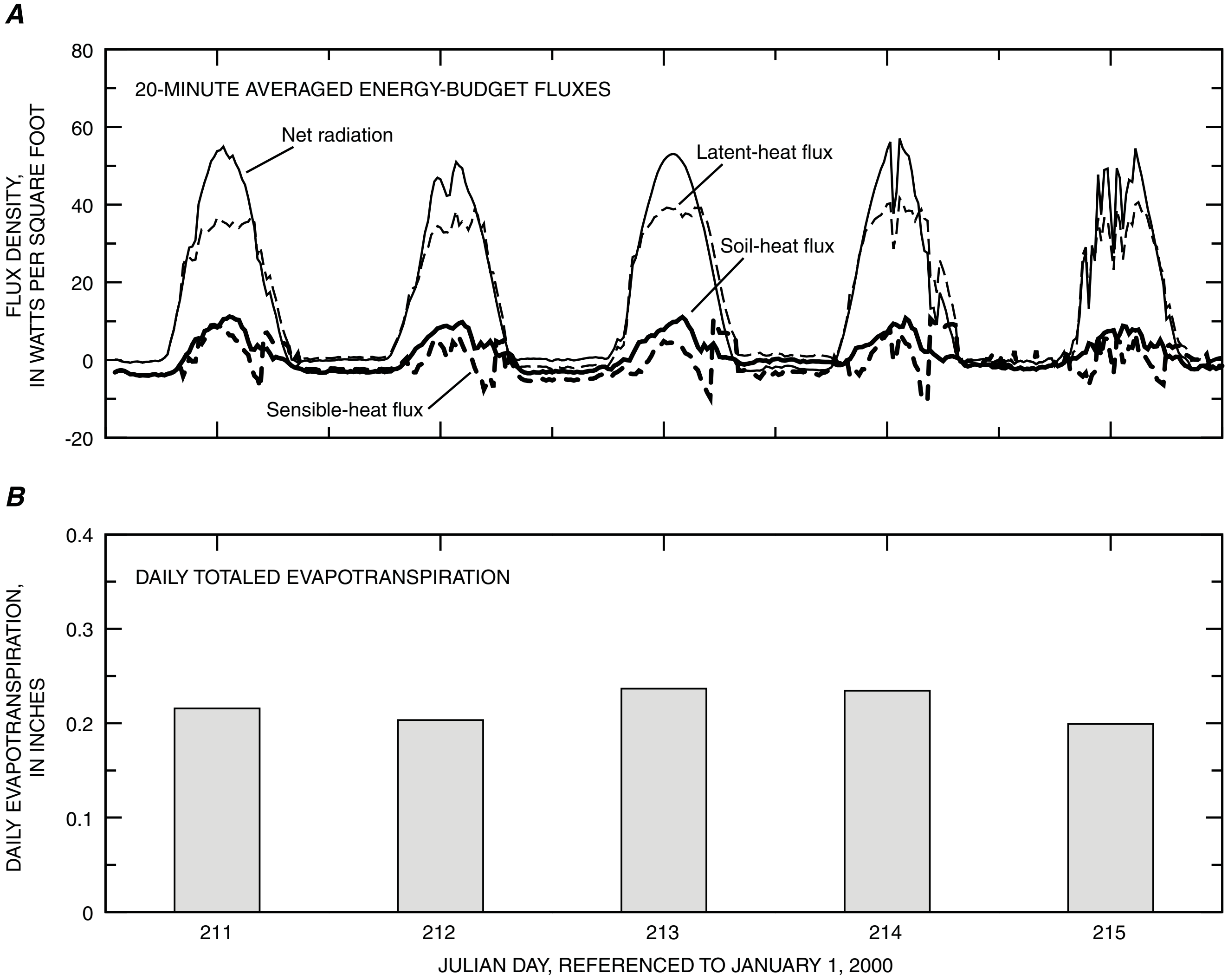


Figure 9. Examples of (*A*) energy-budget fluxes and (*B*) daily evapotranspiration computed with micrometeorological data collected from the Mesquite Flat mixed-grasses site, Death Valley, California, July 29–August 5, 2000.

summed to compute a cumulative ET data set. Gaps in the ET data set were interpolated using Simpson's rule of numerical integration to maintain continuity in the data set and obtain an annual ET rate. A smoothing of the ET data set was done to reduce variability in daily ET that typically is caused by changes in daily weather and associated fluctuations in micrometeorological parameters (fig. 10).

Temporal fluctuations in ET rates are closely related to seasonal conditions such as solar radiation, precipitation, and plant vigor whereas spatial differences in annual ET rates are related to plant density, availability of water, and soil-surface conditions. Daily ET rates at vegetated sites typically are highest in the late spring to early fall because net radiation is at its highest value (fig. 11). Conversely, daily ET rates are lowest from the late fall to early spring months because net radiation is at its lowest values. Similar seasonal fluctuations in daily ET occurred at sites where the environment could not support vegetation, such as the salt and bare-soil playa sites, even though daily ET rates at these sites were significantly less than rates at the vegetated sites.

Annual ET rates for areas of Death Valley span a wide range of values that reflect the diversity of the different environments (fig. 11*B*). Encrusted-salt and bare-soil surfaces that are relatively impermeable and not able to support vegetation typically have very low ET rates. For these non-vegetated sites, total ET ranged from 0.17 ft/yr for the salt playa to 0.21 ft/yr for the

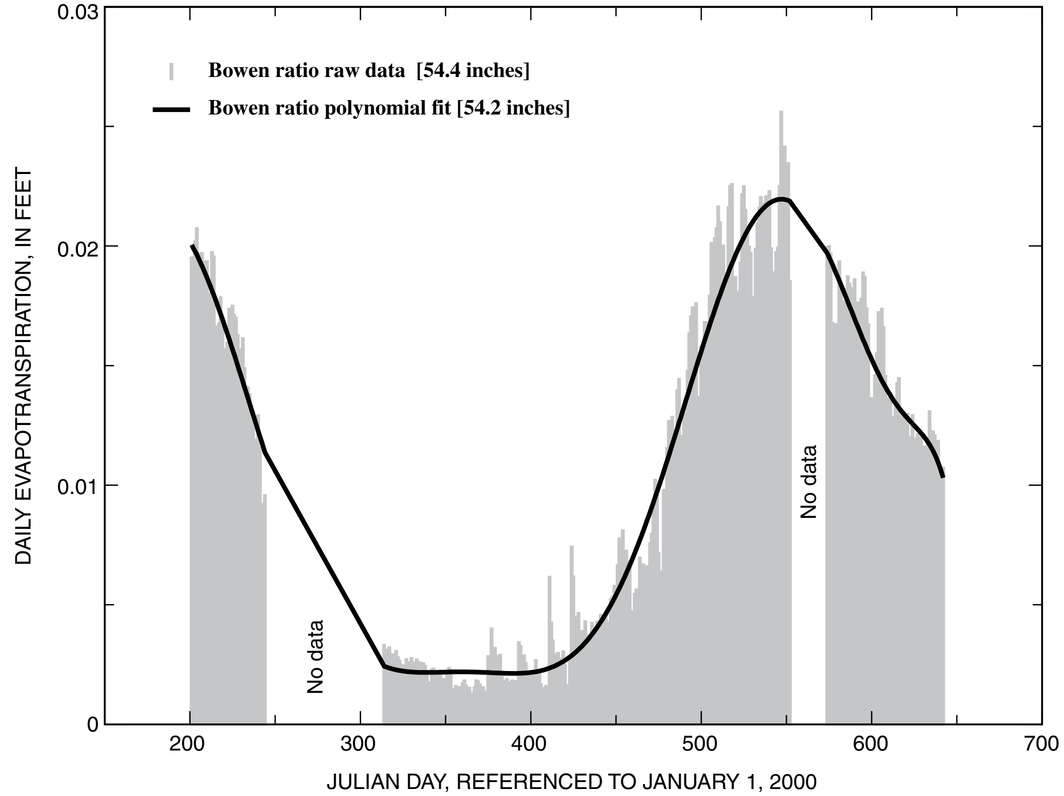


Figure 10. Example of daily evapotranspiration and smoothed fit for data collected at the Mesquite Flat mixed-grasses site, Death Valley, California, July 2000–October 2001.

bare-soil playa (table 3). In other environments where soils can sustain vegetation, ET increases as plant density increases. For these vegetated sites, total ET ranged from 0.60 ft/yr for pickleweed to 3.90 ft/yr Mesquite Flat mixed grasses.

Longer-term micrometeorological data indicate that annual total ET in Death Valley varied as a function of annual precipitation (fig. 11*B*); however, the modest amounts of annual precipitation in Death Valley are not sufficient to sustain local vegetation and account for a very small amount of the measured ET. Therefore native phreatophytic vegetation must survive on local ground water which is the source for the majority of the measured estimated ET.

Comparison of Bowen Ratio and Eddy Correlation Methods

Daily ET rates were estimated for vegetation at the Mesquite Flat mixed-grasses site using the eddy correlation method to compare estimates made with the Bowen ratio method. An independent check of Bowen ratio based ET rates was necessary because of the uncertainty associated with applying energy-budget methods in the extreme climate of Death Valley. Micrometeorological data were collected for the Bowen ratio method from March 2000 to September 2001 and for the eddy correlation method from July 2000 to October 2001.

From March 2000 to September 2001, daily ET values for the Mesquite Flat mixed-grasses site were estimated using equation 6 for Bowen ratio and eddy correlation methods (fig. 12). Using the Bowen ratio method, the minimum daily ET was 0.0 in. on January 7, 2001, and the maximum daily ET was 0.30 in. on June 30, 2001. The average daily ET computed with the Bowen ratio method was 0.10 in., and the total ET for the period was 53.4 in. In comparison, using the eddy correlation method, the minimum daily ET was 0.0 in. on January 9, 2001, and the maximum daily ET was 0.30 in. on June 22, 2001. Using the eddy correlation method, the average daily ET was 0.10 in., and the total ET for the period was 55.4 in. Relatively small discrepancies between Bowen ratio and eddy correlation

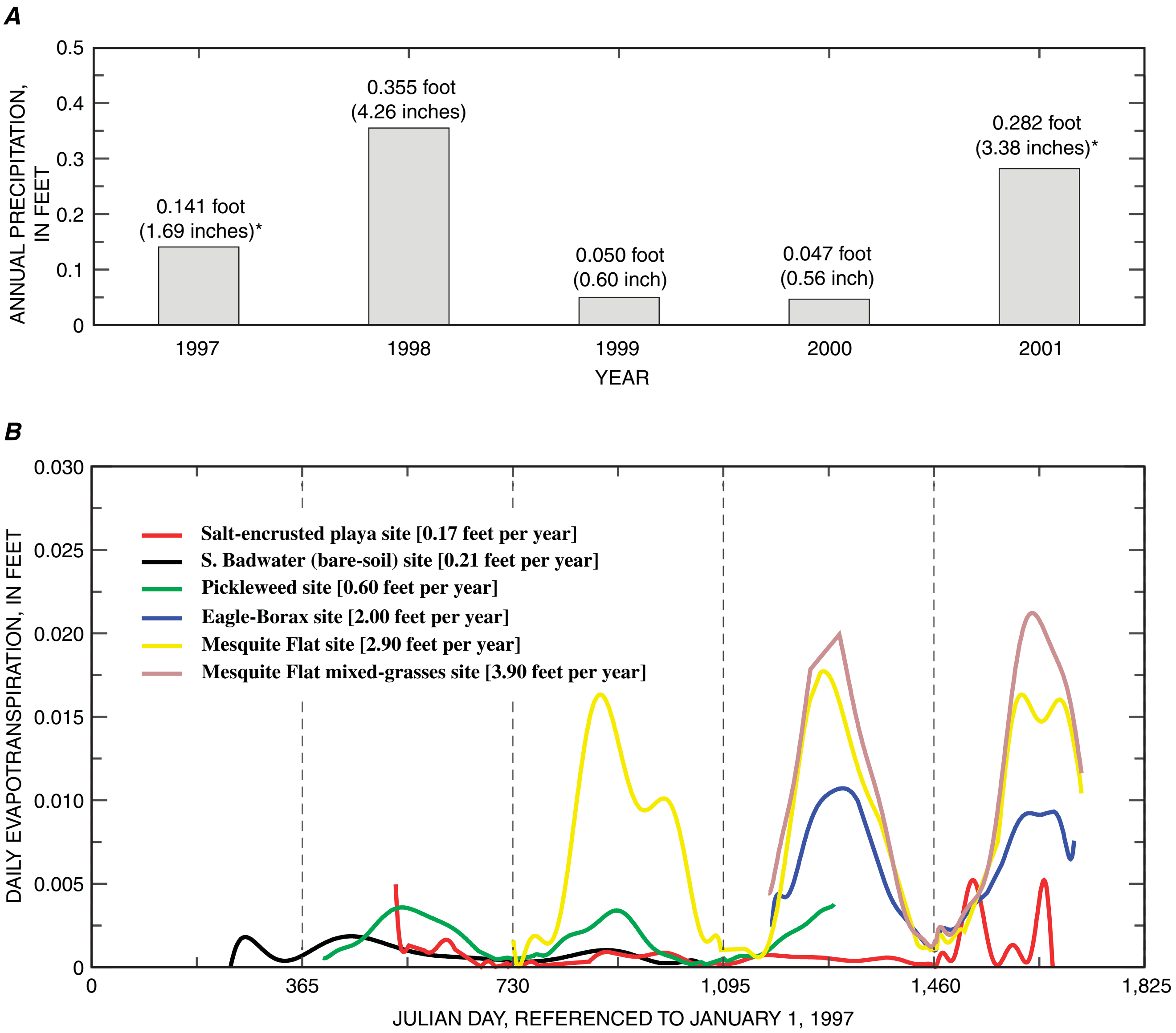


Figure 11. Comparison of (*A*) measured annual precipitation (number above bar is total annual precipitation; asterisk indicates an incomplete year of data) and (*B*) calculated daily evapotranspiration from micrometeorological data-collection sites (bracketed number is estimated annual evapotranspiration for that site), Death Valley, California, 1997–2001.

estimates of ET are owing largely to errors associated with interpolating ET for data gaps caused by short-term Bowen ratio instrument failure.

ESTIMATES OF ANNUAL EVAPOTRANSPIRATION

Estimates of annual ground-water discharge for each ET unit were computed by multiplying acreage of the ET unit by its estimated annual ground-water evapotranspiration rate (table 4). This rate was determined for each site by correcting estimates of annual ET for the effects of precipitation or surface-water inflow to the valley floor. Although shallow ground water is the primary source for ET in Death Valley, local precipitation and flooding of surface-water runoff from areas adjacent to the valley must be accounted for to accurately quantify the amount of ground water discharged by ET. The amount of ground water used for ET annually can be estimated by subtracting local precipitation and surface-water inflow components as expressed by

Table 3. Rates of annual evapotranspiration, measured precipitation, and annual ground-water evapotranspiration at data collection sites in Death Valley, California, 1997–2001

[Abbreviations: ET, evapotranspiration. ET-unit site description: BSP, bare-soil playa; SEP, salt-encrusted playa; LDV, low-density vegetation; MDV, moderate-density vegetation; HDV, high-density vegetation; ET, annual ET rate, annual surface-water and ground-water discharge by ET; ET_{gw}, annual ground-water discharge. Description of ET units listed in table 1]

ET-site name	ET-unit site	Annual ET rate, in feet per year	Annual precipitation, in feet per year	Annual ground-water evapotranspiration rate, in feet per year
Salt-encrusted playa	SEP	0.17 [1]	0.04[1]	0.13[1]
		0.39 [2]	0.28[2]	-1.40 [3]
Bare-soil playa	BSP	0.21[1]	0.06[1]	0.15[1]
		0.37[2]	0.35[2]	0.01[2]
Pickleweed	LDV	0.60	0.06	0.54
Eagle Borax	MDV	2.00	0.23	1.80
Mesquite Flat	HDV	2.90	0.16	2.70
Mesquite Flat mixed grasses	HDV	3.90	0.25	3.60

[1] Data are for years when flooding of the playa did not occur.

[2] Data are for years when flooding of the playa did occur.

[3] Data are for years when flooding of the playa did occur including the quantity of surface-water accumulation resulting from flooding of overland flow not shown in table.

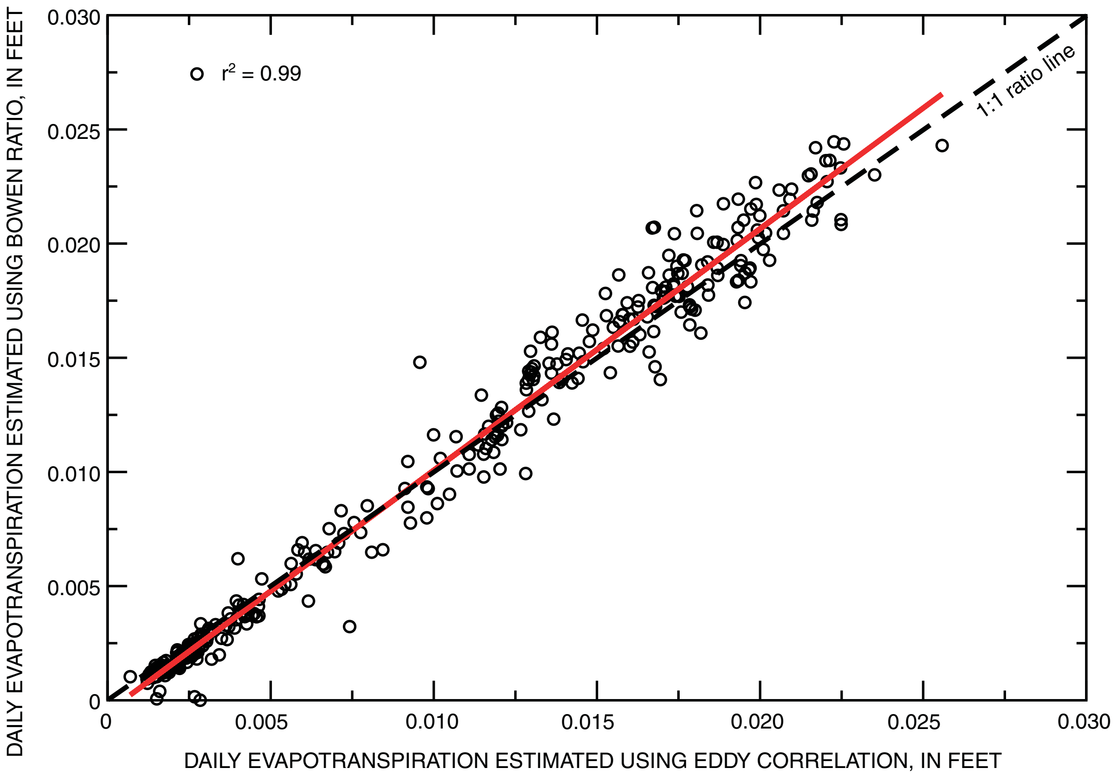


Figure 12. Correlation plot of daily evapotranspiration of Bowen ratio method (Y-axis), and eddy correlation method (X-axis), at Mesquite Flat mixed-grasses site, Death Valley, California, July 2000–October 2001.

$$ET_{gw} = ET - S_w - p \tag{9}$$

where ET_{gw} is annual ground-water evapotranspiration (length),

ET is total estimated annual evapotranspiration (length),

S_w is the quantity of ground- and surface-water accumulation resulting from flooding of overland flow (length), and

p is annual local precipitation (length).

Although it was not possible to precisely determine S_w, approximations were made based on indirect evidence of flooding. For years when flooding did not occur, S_w could be set equal to zero, reducing equation 9 to

$$ET_{gw} = ET - p\,. \tag{10}$$

Table 4. Annual ground-water discharge rate and total annual ground-water discharge for evapotranspiration units, Death Valley, California, 1997-2001

[Abbreviations: ET, evapotranspiration; ET_{gw}, annual ground-water discharge by ET. ET-unit site description: SEP, salt-encrusted playa; BSP, bare-soil playa; LDV, low-density vegetation; MDV, moderate-density vegetation; HDV, high-density vegetation. Description of ET units are listed in table 1]

ET-unit identifier (see table 1)	ET-unit area, in acres	Annual ground-water discharge rate [1], in feet per year	Annual ground-water discharge[1], in acre-feet
BSP	76,000	0.15	11,400
SEP	21,000	0.13	2,730
LDV	6,600	1.0	6,600
MDV	5,000	2.0	10,000
HDV	1,500	3.0	4,500
		Total annual ground-water discharge, in acre-feet	34,800

[1] Data are for years when flooding of the playa did not occur.

Flooding of the Amargosa River (fig. 1) from intense storms made significant contributions to the total ET on the salt and bare-soil playas in 1998 and on the salt playa in 2001. For example, extensive rains in 1998 resulted in flooding of part of the bare-soil playa. No visible evidence of stagnant-flood water existed at the bare-soil playa site but it was apparent that significant over-land flow had occurred due to the heavy rains. As a result, total annual ET for 1998 was relatively high (0.36 ft as compared to 0.21 ft in 1999). By applying equation 10, the ET_{gw} component was determined to be relatively low (0.012 ft).

Heavy rains totaling 0.28 ft were measured between January 1 and July 23, 2001 (204-day period), on the salt playa and lead to extensive flooding of the site (fig. 13). The maximum surface-water depth at the salt-playa site was about 0.57 ft as estimated by the height of salt-crystal deposits on a rain gage (fig. 14). Shallow wells at the site had been removed prior to this wet period, but increases in shallow-water levels resulting from these storms were estimated to be about 1.3 ft. Total ET during this period was estimated at 0.39 ft. Water accumulated from local precipitation and surface-water inflow is assumed to account for the increase in ground- and surface-water levels and totaled 1.84 ft. A total ET_{gw} value of –1.40 ft was calculated using equation 10 and these data. These data demonstrate that precipitation and surface water exceed total ET for the year resulting in ET_{gw} being a negative value. Because all ET was derived from sources other than ground water, ET_{gw} was neglected for this ET unit in 2001.

The results indicate that (1) the volume of available surface water at the salt playa in 2001 exceeded total evaporative discharge and (2) that some surface water may have infiltrated into the shallow aquifer. Excess available surface water may infiltrate on the salt and bare-soil playas or at the margins of the playas, particularly in principal areas of surface-water inflow. In these areas, such as along the Amargosa River and Salt Creek (fig. 2), the permeability of shallow sediment horizons likely is greater than other areas of the playa. However, the uncertainty of estimating available water and potential infiltration on the playa using equation 9 is relatively high. For example, equation 9 does not account for changes in aquifer storage due to rising or falling ground-water levels. Moreover, the accuracy of estimating ungaged surface-water inflow to the salt and bare-soil playas is relatively low.

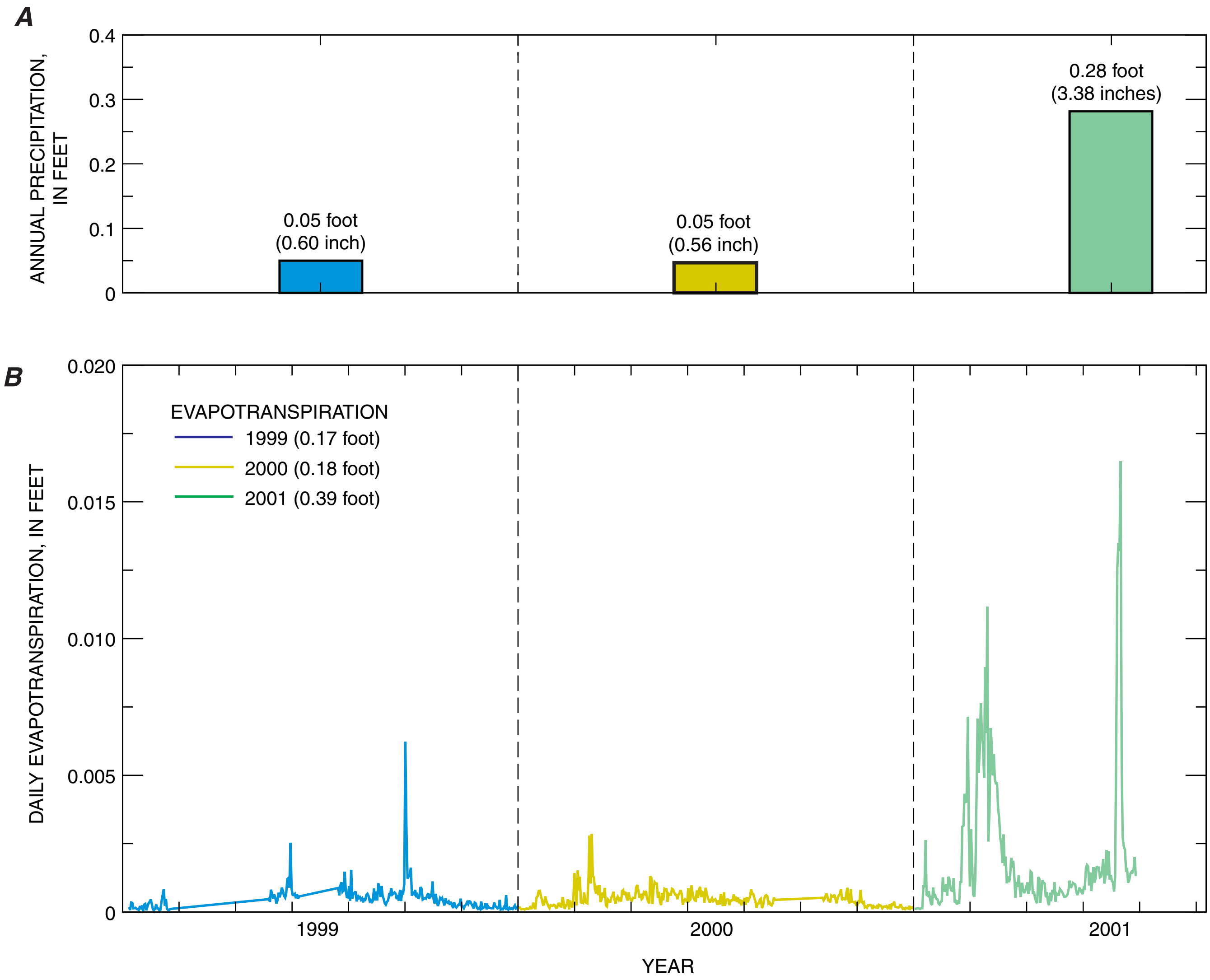


Figure 13. Comparison of (*A*) annual precipitation and (*B*) daily evapotranspiration at the salt-encrusted playa micrometeorological data-collection site, Death Valley, California, January 1999–July 2001.

Long-term flooding conditions (stagnant surface water) were never observed at any of the vegetated ET unit sites. Therefore, annual ground-water discharge at pickleweed, Eagle-Borax, Mesquite Flat, and Mesquite Flat mixed-grasses sites is determined by assuming S_w in equation 9 is equal to zero. Using equation 10, annual ET_{gw} at these sites was estimated by subtracting mean annual precipitation (table 3) from annual ET.

Ground-water discharge for each site is not representative of the entire unit but only of the location where an instrument is placed because each vegetated ET unit spans a spectrum of densities. A plot of ground-water discharge versus relative vegetation cover was constructed to obtain representative rates for each unit. The value at the midpoint of each vegetated ET unit was used as the representative ground-water discharge rate for that unit (fig. 15).

The final estimate of ET_{gw} represents annual ET_{gw} at the corresponding midpoints of low-, moderate-, and high-density ET units and equaled 1.0 ft, 2.0 ft, and 3.0 ft, respectively (table 4). Total ground-water ET from the floor of Death Valley was determined by extrapolating ET_{gw} rates for low-, moderate-, and high-density vegetation using satellite imagery. Therefore, estimates of ET_{gw} computed for each ET unit using equation 10 were adjusted to reflect an average ET_{gw} rate for each vegetation-density group.

Figure 14. Salt-crystal deposits on a rain gage following the evaporation of surface flooding near the salt-encrusted playa micrometeorological data-collection site, Death Valley, California, April 2001.

Estimates of Annual Ground-Water Discharge

Annual ground-water discharge from the valley floor of Death Valley was estimated in this study using data sets of annual ET. All shallow ground-water discharge from the valley floor is assumed to transpire or evaporate from the five delineated ET unit types. Shallow ground-water levels of the valley floor are maintained by periodic infiltration of rainfall and surface flooding from the Amargosa River and Salt Creek (fig. 2), by infiltration of discharge from numerous springs and seeps adjacent to valley floor deposits, and possibly by ground-water underflow from mountains surrounding Death Valley or from the regional carbonate aquifer. Estimates of annual discharge in this report do not include ET from vegetation supported by higher-altitude springs adjacent to the valley floor on the west sides of the Funeral Mountains and Grapevine Mountains (fig. 2).

Estimates of annual ground-water discharge are based on data sets from 1997 through 2001 and represent a very short-term climatic interval. Recorded precipitation ranged from less than 0.08 ft/yr (1 in/yr) to greater than 0.25 ft/yr (3 in/yr). During years of higher precipitation when flooding was observed on the

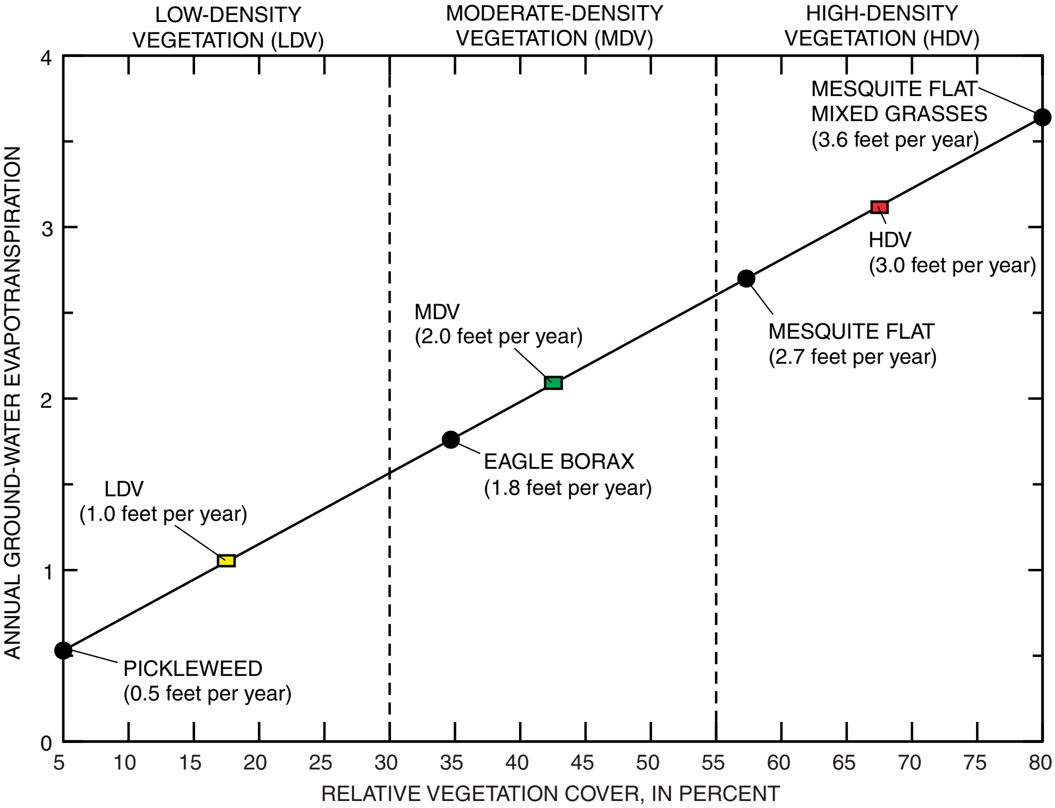


Figure 15. Relation of vegetation density and ground-water evapotranspiration for vegetated evapotranspiration units, Death Valley, California, August 1997–October 2001.

salt and bare-soil playas ground-water discharge from these ET units was considered to be negligible because precipitation and inflow exceeded total ET. For this reason, two estimates of annual ground-water discharge were determined for Death Valley; one representative of a year when flooding did occur on the playas and the other representative of a year when flooding did not occur. These discharge values were then averaged together based on a periodic flood frequency to establish what the annual ground-water discharge would be over time.

Results for years of drier-than-average precipitation conditions (table 3), when flooding on the salt and bare-soil playas did not occur, annual ground-water discharge from the floor of Death Valley was estimated to be about 35,000 acre-ft. Annual ground-water discharge for years of wetter-than-average precipitation conditions, when flooding did occur at the salt and bare-soil playas, was estimated to be less than zero, indicating that the volume of available surface water exceeded total evapotranspiration. During the wetter-than-average period used to calculate annual discharge, ET_{gw} increased slightly (100 to 500 acre-ft) at the vegetated sites. Significant differences in estimated annual discharge between drier- and wetter-than-average years in Death Valley is due primarily to flooding on the playas that contribute most, if not all, water used for ET in these ET units.

Annual ground-water discharge from the valley floor, representative of long-term climatic conditions, was estimated by a weighted-average method using a maximum of 35,000 acre-ft (representing years without playa flooding) and a minimum of 22,000 acre-ft (representing years with playa flooding). Assuming reasonable, but arbitrarily selected, flood frequencies of three-floods in a 20-year period, two-floods in a 10-year period, and one-flood in a 10-year period, annual ground-water discharge was estimated at about 33,000 acre-ft. This result shows that although flooding of the salt and bare-soil playas significantly decreases the annual ground-water discharge these periodic events have little impact on the ground-water discharge over time.

Ground-water discharge estimates from a reconnaissance study (Hunt and others, 1966) and a regional ground-water flow model (Prudic and others, 1995) were compared to results from this study. Although the areas used in these studies differ slightly from the current study, comparisons are useful for presenting a range of possible discharge values and a general understanding of corresponding methods and limitations.

In a study by Hunt and others (1966), annual ground-water discharge was estimated at about 12,900 acre-ft, for an area from Cottonball Basin south to Badwater Basin (fig. 2), based on data collected during winter months between 1957–60. This estimate accounts for discharge from seeps, springs, and vegetated areas along the perimeter of the salt and bare-soil playas and from adjacent mudflat areas on the playas (about 8,800 acre-ft/yr). Hunt's estimate also accounts for discharge from Travertine Springs complex, and Texas and Narvares Springs on the west sides of the Funeral and Grapevine Mountains (fig. 2) along the eastern margin of the valley (about 4,100 acre-ft/yr). This estimate does not include discharge by ground-water evaporation from much of the salt-encrusted and bare-soil playas or from Mesquite Flat (fig. 2). For the current study, annual ground-water discharge from the valley floor between Cottonball Basin and Badwater Basin was estimated at 24,000 acre-ft. Not including discharge from springs along the eastern margin of the valley, the estimate of discharge by Hunt and others (1966) is about two and a half times less than estimated ground-water discharge for the current study. Differences between these discharge estimates are largely due to differences in the ET rates applied and the acreage of application.

Limitations

Underlying limitations and assumptions in the methods and techniques used in this study may affect the accuracy of estimated total annual ground-water discharge from the floor of Death Valley. One limitation in applying the Bowen ratio method is the advection of air from ET units other than the one being sampled (Ohmura, 1982). Uncertainties resulting from difficulties in the Bowen ratio likely were small because (1) sites were carefully located within areas of relatively large fetch and (2) instrument bias was minimized by using an automatic exchange mechanism to alternate the positions of the THPs between reference heights twice in a data collection period.

ET rates computed with data collected from six sites over a relatively short period of time were assumed to adequately represent the hydrologic and meteorological conditions in Death Valley. These rates vary spatially from changes related to soil cover and vegetation type, and density as well as temporally from changes in vegetation density and vigor. These changes in land-surface cover are responses to cycles in climate. To account for the variations in land-surface cover satellite-imagery data for a 3-year period were applied so that wet-and-dry conditions in Death Valley were used in the final analysis. These satellite data, however, were from years other than when field data were collected creating some uncertainty as to the actual acreages of the ET units.

Runoff from storms will periodically flood areas of the valley floor. However, the magnitude and frequency of the flooding are unable to be quantified because drainages from valley margins are not gaged.

SUMMARY

The USGS, in cooperation with the NPS and Inyo County, California, conducted a study from 1997 through 2001 to improve estimates of the amount of ground water naturally discharged by ET from the floor of Death Valley. Relatively large amounts of ground water are discharged by vapor flux through areas of salt-encrusted and bare-soil playas on the valley floor and by transpiration from areas of phreatophytic vegetation primarily along the western margin of the valley, in Mesquite Flat, and adjacent to reaches of the Amargosa River.

Satellite-imagery data and results from the NWI were used to identify areas with significant rates of ET on the valley floor and to delineate these areas into zones of similar vegetation and soil characteristics (known as ET units). Five unique ET units were identified: salt-encrusted playa (21,287 acres), bare-soil playa (75,922 acres), low-density vegetation (6,525 acres), moderate-density vegetation (5,019 acres), and high-density vegetation (1,522 acres). A sixth ET unit, open water, had been considered for the final results, however, with a total area of only 2 acres annual ET is estimated to be only 17 acre-ft. This estimate is less than two thousandths of the total ground-water discharge for the entire study area and is not included within the final result.

Representative ET rates for salt-encrusted playa, bare-soil playa, low-density vegetation, moderate-density vegetation, and high-density vegetation were computed by collecting micrometeorological data at instrumented sites within these ET units and solving an energy-budget equation using the Bowen ratio method. Daily ET rates were determined at each site by summing 20-minute averaged values computed with micrometeorological data sampled at intervals between 10 and 30 seconds. Annual ET rates for ET units ranged between 0.17 ft for the salt playa and 3.89 ft for dense vegetation.

The amount of annual ground-water discharge by ET from the floor of Death Valley as estimated in this study is 35,000 acre-ft and was computed by multiplying the area of each ET unit by its corresponding annual ET rate adjusted for annual rainfall.

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