Ground-Water Discharge by Evapotranspiration in a Desert Environment of Southern Nevada, 1987

By MICHAEL J. JOHNSON

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Area	
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
	Density	
kilogram per cubic meter (kg/m^3)	0.06244	pound per cubic foot
	Energy	
joule (J)	0.0009479	British thermal unit
	Energy flux	
watt per square meter (W/m^2)	0.005286	British thermal unit per square foot
	Evapotranspiration rates	
millimeter per hour (mm/h)	0.03937	inch per hour
millimeter per day (mm/d)	0.03937	inch per day
millimeter per year (mm/yr)	0.003281	foot per year
	Heat of vaporization	
joule per kilogram (J/kg)	0.0004303	British thermal unit per pound
	Length	
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Mass	
kilogram (kg)	2.205	pound
	Mass flux	
kilogram per square meter per second [$(kg/m^2)/s$]	12.29	pound per square foot per second
	Power	
watt (W)	3.413	British thermal unit per hour
	Slope function and psychrometer constant	
kilogram per cubic meter per degree Celsius [$(kg/m^3)/^{\circ}C$]	0.03469	pound per cubic foot per degree Fahrenheit
	Transport resistance	
second per meter (s/m)	0.3048	second per foot
	Velocity or rate	
meter per second (m/s)	2.237	mile per hour
	Volume	
cubic meter (m^3)	35.31	cubic foot
cubic hectometer (hm^3)	810.7	acre-foot
	Volumetric water content	
gram per cubic centimeter (g/cm^3)	0.5269	ounce per cubic inch

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32). Kelvins (K) can be converted to degrees Fahrenheit by using the formula °F = (K-273.15)1.8+32.

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

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ABSTRACT

Evapotranspiration data were collected at two sites where microclimates are typical of the Mojave Desert in southern Nevada—one site with and one without ground-water contributions to evapotranspiration—under extremely arid desert conditions. By comparing the rate of evapotranspiration at the two sites, the amount of ground water discharged by evapotranspiration can be inferred. This method may be useful for quantifying ground-water discharge around basin playas or springs.

Continuous 30-minute measurements of eight meteorological variables recorded for a 12-month period starting in October 1986 were used to define the microclimate at the two contrasting desert sites west and northwest of Las Vegas, Nevada. Daily and 30-minute trends in solar radiation, net radiation, soil-heat flux, windspeed and direction, air temperature, relative humidity, and precipitation were used to characterize the climate. Daily average air temperatures ranged from -3 to 32 degrees Celsius during the period of study. Summer daytime temperatures generally exceeded 35 degrees Celsius. Monthly precipitation ranged from 0 to 124 millimeters. Residual moisture after each storm affected background relative-humidity values for 1 to 3 days. Typical afternoon relative humidities were generally about 15 percent in the spring and 10 percent or less in the summer. Daily solar radiation over the 12-month period ranged from 17 to 574 watts per square meter. The maximum net radiation during a summer day generally was highest 2 to 4 hours before the maximum vapor-pressure deficit.

The eddy-correlation method was used to estimate 30-minute averages of latent- and sensible-heat fluxes. Latent-heat fluxes were summed to obtain daily evapotranspiration. Results using the eddy-correlation method for deriving evapotranspiration were in close agreement with, but generally less than, results obtained using the latent-heat-flux residual derived from the energy-budget equation. At the site with ground-water contributions, potential evapotranspiration estimated by the Penman-combination method was comparable to actual evapotranspiration only during summer conditions without wind. Under windy conditions with hot summer temperatures, the potential evapotranspiration exceeded the actual evapotranspiration by as much as six times, suggesting that plant transpiration rates and unsaturated soil hydraulic conductivity could not supply enough water to meet the peak demand periods of water vaporization under these conditions. At the other site, which has no ground-water contribution, potential evapotranspiration consistently exceeded actual evapotranspiration, indicating that there was insufficient water to meet the energy requirement for vaporization of moisture. The combined evapotranspiration rates measured at both sites during the spring and summer of 1987 indicated that actual evapotranspiration ranged from 0.0 to 0.4 millimeter per hour and 0.01 to 6.3 millimeters per day.

Comparison of monthly evapotranspiration totals based on average daily rates at the two sites indicates that about 520 millimeters of ground water was lost to evapotranspiration at Ash Meadows during the 6 months of record, April through September 1987. This is in general agreement with the range of values estimated for areas with native vegetation in the Amargosa Desert where the depth to water was between 0.0 and 1.5 meters. Estimated rates ranged from 320 to 760 millimeters per year.

INTRODUCTION

During 1985-89, the U.S. Geological Survey did an intensive study of the carbonate-rock aquifer systems of eastern and southern Nevada, in cooperation with the State of Nevada, other federal agencies, and the Las Vegas Valley Water District, to better understand these large, regional aquifers and to explore their potential for water supply. The carbonate-rock aquifer study included an evaluation of the effects of both short- and long-term development on discharge from the carbonate aquifers. Discharge processes include subsurface flow from one topographic basin to another, spring discharge, and evapotranspiration (*ET*). Because a major source of natural ground-water loss in arid regions is by evapotranspiration from both spring discharge and shallow ground-water discharge through bare soil evaporation and plant transpiration, part of the carbonate-aquifer study included an investigation of the mechanisms and rates of *ET* discharge. This part of the carbonate-aquifer study to evaluate *ET* was a cooperative effort between the Geological Survey and the State of Nevada.

The accuracy with which *ET* discharge can be determined directly affects the validity of the water budgets prepared for the region. Accurate determinations will help to identify the effects that discharge from the carbonate aquifers have on the natural environment. Although discharge from carbonate aquifers that surfaces at springs can be measured directly, shallow ground water from carbonate aquifers that evaporates in lower parts of the topographic basin or adjacent to areas with springs is more difficult to evaluate and to separate from *ET* derived from noncarbonate water sources. These noncarbonate sources can include ground water from basin-fill deposits, soil moisture derived from overland flow or local precipitation, and water derived from water vapor present in the air that is absorbed by the plants and soils.

As part of the larger investigation of ground-water flow in southern Nevada, a reconnaissance study was made and data were collected to obtain initial *ET* rates for evaluating the discharge component of the water budget. Although *ET* is a major source of natural ground-water discharge in this arid region, few measurements have been made in southern Nevada to define the *ET* component of the water budget or to identify that part of the *ET* component of the water budget that represents ground-water discharge.

Purpose and Scope

This report describes the interpreted results of a study to determine if *ET* measurements could be made under extreme arid conditions, and to measure *ET* rates at a limited number of sites during the summer of 1987 in southern Nevada. This preliminary information is used with other data to better understand available energy and water-vapor losses related to evapotranspiration, and to observe *ET* rates in the Mojave Desert of southern Nevada. A previous report (Johnson, 1993) describes the data collection, processing, and storage techniques.

Two sites were selected—one with and one without ground-water contributions to *ET*—to identify the potential range of *ET* values typical of this part of Nevada. Electronic instruments were used at the sites to measure the micrometeorological variables necessary to calculate actual *ET* using the eddy-correlation method and to calculate potential *ET* using the Penman-combination method. The measurements were made April through September 1987; micrometeorological measurements were for a 12-month period beginning in October 1986.

Geological and Climatological Settings

The two study sites (fig. 1) were chosen for their contrasting microclimates, with and without ground-water contributions to *ET*, under extreme, arid desert conditions. The site with a ground-water contribution is at Ash Meadows in the southern part of the Amargosa Desert (latitude 36°25'11", longitude 116°20'29"), about 110 km west of Las Vegas. The site without a ground-water contribution is in the northwestern part of Las Vegas Valley (latitude 36°28'26", longitude 115°24'11"), about 40 km northwest of Las Vegas near Corn Creek Springs. Ash Meadows is a regional spring-discharge area with an estimated average annual discharge of 21 hm^3 (Walker and Eakin, 1963, p. 21) supplied by an extensive system of carbonate-rock aquifers to the north and east. The Ash Meadows *ET* station was located in a large meadow containing moist subsoils, a dense, short meadow grass understory, and sparse, low-lying shrubs. Depth to the water table was generally 1 to 2.5 m, providing good conditions for ground-water contributions to *ET*. The northwestern Las Vegas Valley *ET* station near Corn Creek Springs, a spring

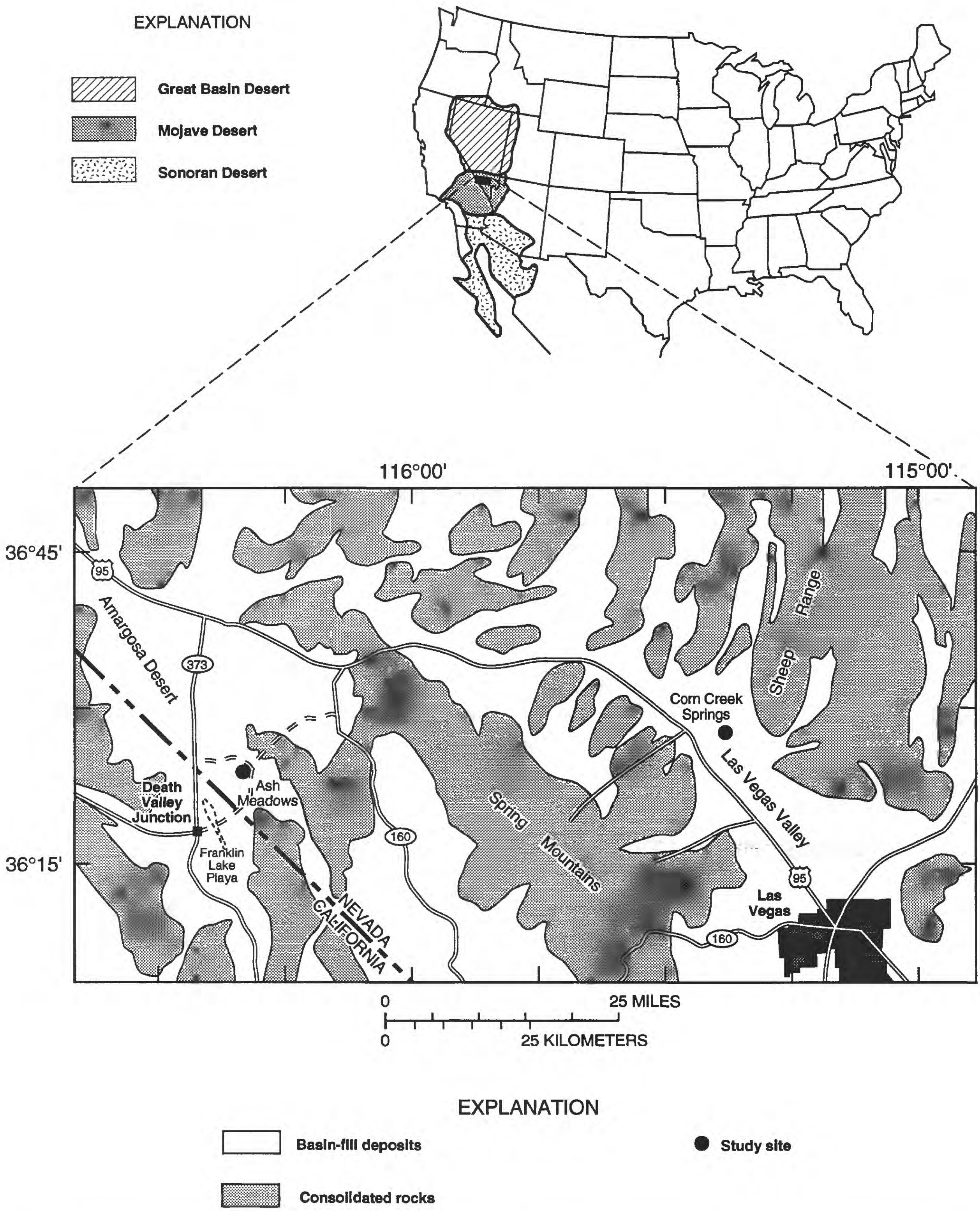

Figure 1. Evapotranspiration sites at Ash Meadows and northwest Las Vegas Valley. Desert areas modified from MacMahon (1985).

locally discharging about 0.27 hm^3 (Pupacko and others, 1989), represented a site that had no detectable ground-water contribution to *ET*, based on neutron activation analysis of soil moisture at depth. The northwestern Las Vegas Valley *ET* station was on bare, dry soils with a 25-percent canopy coverage of low-lying forbs and nonphreatophytic shrubs. Depth to the water table was more than 8 m below the land surface. The Ash Meadows and northwestern Las Vegas Valley sites are at altitudes of 660 and 911 m respectively.

Both study sites are in the Mojave Desert region of southern Nevada (fig. 1). The topography consists of mountain ranges separated by basins that are generally drained internally and contain playas. The Mojave Desert is considered transitional both in physiography and in vegetation because it straddles two separate sections of the Basin and Range Physiographic Province—the Great Basin Desert to the north and the Sonoran Desert to the south (fig. 1; MacMahon, 1985). Frost-free days in the Mojave Desert commonly exceed 200 per year. Diurnal temperature changes of 25°C are common, and summer temperatures often approach 50°C.

In the Mojave Desert, precipitation falls as winter precipitation from regional storms originating in the Pacific Ocean and summer rains from convective thunderstorms of high intensity, short duration (minutes to hours), and limited areal extent. From 65 to 98 percent of the total scant precipitation occurs in winter. Mean annual precipitation for most sites is less than 150 mm. Across the Mojave Desert of southern Nevada, the average annual precipitation is typically 105 mm in Las Vegas Valley at Las Vegas, Nevada, but drops to less than 50 mm with some years that have no recorded rainfall in the Death Valley portion of the Amargosa Desert. Because relative humidity varies inversely with temperature, the winters in the desert are more humid than the summers. With limited rainfall, fog and dew can be a significant source of winter moisture for plants and animals. Plant growth is dominated by low, widely spaced shrubs in response to sparse moisture in this desert.

Warm temperatures and high winds cause high evaporation rates that adversely affect native plants and animals. Evaporation from an exposed water surface in this desert environment can range from 1,800 to 4,000 mm/yr (MacMahon, 1985); pan evaporation at Boulder City near Las Vegas is typically 2,800 mm/yr (National Oceanic and Atmospheric Administration, 1982). The annual precipitation of 150 mm is much less than the potential evaporation, as much as 4,000 mm/yr, in the Mojave Desert.

METHODS OF ESTIMATING EVAPOTRANSPIRATION

The net transfer of energy at the surface of the Earth can be expressed in terms of the energy budget. The energy available at the ground surface is the difference between total downward and total upward radiation fluxes. This net radiation flux is composed of the algebraic sum of the short-wave radiation from the Sun in the form of direct or atmospherically diffused radiation, minus its reflected short-wave component, plus the incoming long-wave radiation from the atmosphere, minus the upwelling, long-wave terrestrial radiation from the surface of the Earth.

Net radiation is the fundamental quantity of energy available at the surface of the Earth to supply energy for the process of evapotranspiration (latent-heat flux), to warm the air (sensible-heat flux), and to heat the soil (soil-heat flux), as well as for other, less energy-consuming processes. Excluding the minor amount of energy expended for photosynthesis and plant respiration, the energy budget at the surface of the Earth can be expressed by the relations between the major energy-flux densities with the following equation:

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

where

- R_n is net radiation (watts per square meter)
- G is soil-heat-flux density (watts per square meter)
- H is sensible-heat-flux density (watts per square meter)
- λE is latent-heat-flux density (watts per square meter)
- λ is latent heat of vaporization (joules per kilogram)
- E is water-vapor-flux density (kilograms per square meter per second).

To apply the energy-budget equation, a horizontal layer is established, with an upper boundary just above the plant canopy and a lower boundary just below the soil surface. The energy-flux densities (R_n, G, H, and λE) entering and leaving the layer are measured and substituted into equation 1 to confirm the equality.

Eddy-Correlation Method

The eddy-correlation method measures the turbulent fluxes of latent and sensible heat from covariances, as initially developed by Brutsaert (1982). The results of studies in which the eddy-correlation method has been used in the western deserts of the United States are presented in Duell and Nork (1985), Duell (1985; 1990), and Stannard (1987).

In the eddy-correlation method, both the latent- and sensible-heat fluxes can be calculated. Latent-heat flux (λE), a direct measurement of actual *ET*, is calculated from the covariance of vapor density and vertical windspeed fluctuations. Sensible-heat flux (H) is calculated from the covariance of vertical windspeed and air-temperature fluctuations. The eddy-correlation flux equations are (Campbell, 1977, p. 37):

$$\lambda E = \overline{V'W'}\lambda, \qquad (2)$$

and

$$H = \overline{W'T'}\rho_a C_p, \qquad (3)$$

where

- ′ is the instantaneous deviation from the mean
- — is the average for a given period (in this case, 5 minutes)
- V is vapor density of air (kilograms per cubic meter)
- W is vertical wind velocity (meters per second)
- T is temperature of air (degrees Celsius)
- ρ_a is density of air (kilograms per cubic meter)
- C_p is specific heat of air (joules per kilogram per degree Celsius).

The sum of the two turbulent fluxes shown in equations 2 and 3 should equal the net radiation less the soil-heat flux, as defined in the energy-budget equation (eqn. 1). Because of measurement and instrumental errors, the energy-budget equation does not always balance. To measure the relative balance or closure, Duell (1985) suggests calculating the ratio of the turbulent fluxes to the available energy, called the energy-budget closure (EBC):

$$\text{EBC} = \frac{\lambda E + H}{R_n - G} \times 100 \cdot \qquad (4)$$

In the eddy-correlation method, the actual *ET* can be obtained directly from measurements of just the latent-heat flux obtained from equation 2, without consideration of the other three energy-budget components. The eddy-correlation method also permits actual *ET* to be estimated from the energy-budget equation (eqn. 1) by measuring sensible-heat flux obtained from equation 3, net radiation, and soil-heat flux, and then calculating the latent-heat flux (λE) as a residual (α):

$$\alpha = \lambda E = R_n - G - H \ . \qquad (5)$$

The data collected in this study allow the calculation of actual *ET* either by direct measurements of the latent-heat flux or by calculation of the latent-heat flux residual. The data also permit the calculation of the energy-budget closure using equation 4.

Penman-Combination Method

Estimates of potential *ET* also were calculated. Penman (1948) was the first to develop a combination equation. The original Penman potential-*ET* equation (Penman, 1956) is based on the assumption that canopy resistance to atmospheric heat and vapor diffusion are equal. Many equations are available for estimating potential *ET* from climatic data; the Penman-combination equation (Campbell, 1977, p. 138) was used in this study:

$$\lambda E_p = \frac{\left(\dfrac{S(R_n - G) + \rho_a C_p (\rho_{v_s} - \rho_v)}{r_H}\right)}{\gamma + S}, \qquad (6)$$

where

- λE_p is potential latent-heat flux (watts per square meter)
- S is slope of the saturated-vapor density function (kilograms per cubic meter per degree Celsius)
- γ is thermodynamic-psychrometer constant (kilograms per cubic meter per degree Celsius)

ρ_{v_s} is saturated water-vapor density at the existing temperature (kilograms per cubic meter)

ρ_v is water-vapor density (kilograms per cubic meter)

r_H is sensible-heat-transport resistance (seconds per meter).

The sensible-heat transport resistance (r_H) can be calculated (Campbell, 1977, p. 138) as

$$r_H = \frac{\ln\left(\frac{z-d+z_h}{z_h}\right)\ln\left(\frac{z-d+z_m}{z_m}\right)}{k^2\bar{u}}, \quad (7)$$

where

z is height of measurements above soil surface

z_m is roughness parameter for momentum (0.13 h, where h is average crop canopy height)

z_h is roughness parameter for heat (0.2 z_m)

d is zero plane displacement, obtained from $\log d = 0.9793 \log h - 0.1536$ (Stanhill, 1969, p. 153)

k is unitless von Karman constant (0.4)

$\bar{u}$ is mean windspeed (meters per second at height z).

The Penman-combination equation is valid for dense, well-watered crop canopies where the heat-exchange surface is the vapor-exchange surface. When both exchange surfaces are the same, actual *ET* is at a minimum and comparable to potential *ET* as defined in the Penman-combination equation. As a vegetated surface dries, however, the vapor-transport resistance is not equal to, but is greater than, the resistance to heat transport. In addition, in arid regions, incomplete cover and the type of vegetation make this difference in resistance even greater. Thus, actual *ET* is much less than potential *ET* in arid regions, and actual *ET* can not attain the potential *ET* rates as defined by Penman (1948).

An improvement to the Penman-combination equation is the Penman-Monteith equation (Monteith, 1973), which accounts for the effects of drying, thus giving a closer estimate of actual *ET*. In the Penman-Monteith equation, the thermo-dynamic psychrometer constant in the Penman-combination equation is replaced by the apparent psychrometer constant (Campbell, 1977, p. 137):

$$\gamma^* = \gamma(r_v/r_H), \quad (8)$$

where

γ^* is apparent psychrometer constant (kilograms per cubic meter per degree Celsius)

γ is thermodynamic psychrometer constant (kilograms per cubic meter per degree Celsius)

r_v is vapor-transport resistance (seconds per meter)

r_H is heat-transport resistance (seconds per meter).

Thus, the Monteith combination equation does not assume that the canopy resistance to atmospheric sensible heat and vapor transport are equal. An estimate of the vapor-transport resistance (r_v) can be obtained by using directly measured latent-heat flux, or the latent-heat-flux residual, in the Penman-Monteith combination equation, along with the sensible-heat-transport resistance. Thus, if r_v is a predictable function, the Penman-Monteith combination equation can be used to extrapolate estimates of actual *ET* when direct measurements of latent-heat flux are not available in the field, but climatic data are available. From the field data collected for this study, the vapor-transport resistance was calculated using the measured latent-heat flux.

INSTRUMENTATION AND DATA PROCESSING

The eight variables used to characterize the microclimate at each *ET* site from October 1986 to September 1987 were measured as follows:

Incoming short-wave solar radiation was measured with a Li-Cor silicon pyranometer mounted about 2.5 m above the ground. Net radiation was measured approximately 1.0 m above the ground using a temperature-compensated Fritchen net radiometer. Soil-heat flux was measured with soil-heat flux disks at a depth of 5 mm below the soil surface to minimize losses to heat storage in the soil above the sensor. A potentiometric wind vane, mounted 2 m above ground surface, was used to determine wind direction.

Horizontal windspeed was measured at the same height using a three-cup anemometer. Air temperature and relative humidity were monitored from a single probe mounted 1.5 m above the ground. The probe contained a Phys-Chemical Research RH sensor and a Fenwal Electronics thermistor configured for use with the data logger. Precipitation was measured with a tipping-bucket raingage.

For the eddy-correlation measurements obtained at each *ET* site during the spring and summer of 1987, the variance in vertical windspeed and temperature was measured using a sonic anemometer and a fine-wire thermocouple, while vapor-density measurements were made with a Lyman-Alpha hygrometer.

Measurements for estimating potential *ET* were collected continuously throughout the month using meteorological variables; measurements for obtaining actual *ET* commonly were collected for continuous 10-day periods each month by setting up and removing the eddy equipment. At each site, the daily data available for comparing potential and actual *ET* ranged from 2 to 8 days each month due to data losses. Data loss was increased because of unexpected precipitation, which corroded (electrically shorted) the sensors of the sonic anemometers or caused air-vapor densities to increase beyond the adjusted range of the Lyman-Alpha hygrometer previously set for arid desert conditions. At times, static electricity induced high-voltage spikes within equipment circuits and within the solid-state chips of the field recorder even with recommended grounding. This caused circuit paralysis or erroneous data values.

Meteorologic variables were scanned every 60 seconds and turbulent flux variables used for the eddy-correlation method were scanned every 0.1 second using a Campbell Scientific CR-21X micrologger. Meteorological data were accumulated, processed, and stored at 30-minute intervals. The eddy-correlation covariance values were calculated every 5 minutes and averaged into 30-minute intervals.

The computer program, equations, and parameters used to estimate potential and actual *ET*, and to reformat the meteorologic data and *ET* values into daily tables with 30-minute readings, daily averages and sums for final storage, is described by Johnson (1993). That report also discusses the equipment used and its accuracy, maintenance, and limitations.

RESULTS AND DISCUSSION

Microclimatological Characteristics

Tables 1 and 2 list the variables measured to characterize the microclimates at the two study sites. The data illustrate the range, duration, and seasonal fluctuation of the microclimate variables for 12 months starting in October 1986. Files containing the basic field data, the processed data tables, and the computer programs used to process the data were published previously (Johnson, 1993).

Incoming solar radiation measured at each site during a 1-year period (Oct. 1986 through Sept. 1987) indicated average daily values of about 310 W/m^2. The average daily solar radiation measured at both sites in July 1987 was about 480 W/m^2, compared to about 100 W/m^2 in December 1986. The average net radiation recorded during the 6-month period from April through September 1987 was 239 W/m^2 at Ash Meadows and 173 W/m^2 at Las Vegas Valley. The net radiation during the 6-month period was typically 52 percent of the solar radiation at Ash Meadows and 41 percent at Las Vegas Valley. Daily soil-heat flux was generally one or more orders of magnitude smaller than the daily net radiation. The diurnal changes in the soil-heat flux were significantly larger at the Las Vegas site, where vegetation was sparse over dry exposed soils, allowing for greater daytime surface heating and reradiation at night.

Total precipitation for the year of record was 553 mm at Ash Meadows and 603 mm at northwest Las Vegas Valley. The period was abnormally wet for an area where annual precipitation is commonly less than 127 mm. Major winter and spring Pacific storms supplied a regional source of unusually persistent "rain-band" precipitation, followed by spring and summer thunderstorms with locally intense precipitation. Maximum relative humidity was recorded immediately after these storms. Normal afternoon relative humidity of typically less than 15 percent returned within 2 to 3 days after each spring storm. In the summer months, typical daytime relative humidities of about 10 percent were reached within a day or two after a storm. These summer storms tended to lower the average monthly air temperatures, due to increased cloud cover and reduced solar radiation. Still, summer daily averages at both sites were 28°C, and afternoon temperatures commonly exceeded 35°C. The maximum recorded temperature of 42°C at both sites was on July 14, 1987, at 1500-1530 hours.

Table 1. Characterization of microclimate at Ash Meadows, Nev., a desert site with a ground-water contribution to evapotranspiration, October 1986-September 1987

[Abbreviations: W/m^2, watt per square meter; m/s, meter per second; °C, degree Celsius; m, meter; mm, millimeter; NA, not available; SW, southwest; NW, northwest; NE, northeast; SE, southeast; <, less than. For monthly averages, number of days of record is indicated within parentheses; for maximum and minimum daily averages, day of month is indicated within brackets; for maximum and minimum extremes, day of month and hour of day are indicated within brackets]

	October	November	December	January	February	March
Solar radiation (W/m^2)						
Monthly average	147.7 (25 days)	144.9 (28 days)	108.3 (29 days)	132.1 (30 days)	236.0 (26 days)	342.5 (29 days)
Maximum daily average	209.7 [12]	172.4 [12]	146.2 [01]	163.5 [31]	348.9 [27]	463.0 [29]
Minimum daily average	37.3 [02]	41.4 [18]	34.2 [06]	16.9 [04]	96.7 [02]	108.2 [05]
Net radiation (W/m^2)						
Monthly average	NA	NA	NA	NA	NA	216.7 (26 days)
Soil-heat flux (W/m^2)						
Monthly average	1.0 (25 days)	2.5 (28 days)	-2.5 (29 days)	-1.9 (30 days)	-0.6 (26 days)	-0.2 (31 days)
Maximum daily average	6.6 [30]	10.4 [02]	3.0 [06]	7.5 [27]	6.8 [05]	8.0 [03]
Minimum daily average	-3.2 [20]	-2.6 [21]	-7.5 [14]	-7.7 [12]	-8.6 [27]	-7.2 [19]
Horizontal windspeed (m/s)						
Monthly average	1.6 (25 days)	1.9 (28 days)	0.9 (29 days)	2.3 (30 days)	1.9 (30 days)	2.2 (29 days)
Maximum daily average	4.1 [31]	6.1 [29]	4.0 [07]	6.8 [16]	4.6 [27]	4.9 [27]
Minimum daily average	.3 [07]	.2 [18]	.1 [14]	.2 [22]	.2 [11]	.3 [02]
Maximum [extreme]	8.4 [01;2000]	9.9 [29;1300]	7.2 [07;1100]	9.5 [28;0900]	10.6 [23;1500]	9.7 [22;1130]
Wind direction						
Azimuth of maximum speed	SW	SW	SW	NW	NW	NW
Percent time from:						
NE quadrant	15	18	23	23	17	4
SE quadrant	5	7	11	5	1	1
SW quadrant	46	52	47	52	42	20
NW quadrant	34	23	19	20	40	75
Air temperature at 1.0 m (°C)						
Monthly average	16.1 (13 days)	11.2 (28 days)	5.1 (29 days)	5.0 (31 days)	9.0 (28 days)	11.0 (31 days)
Maximum daily average	20.3 [30]	17.3 [03]	10.4 [06]	14.1 [28]	14.3 [10]	16.5 [04]
Minimum daily average	12.4 [20]	6.5 [08]	-.1 [14]	-.2 [16]	2.0 [25]	5.0 [15]
Maximum [extreme]	29.8 [29;1500]	28.0 [03;1600]	19.4 [17;1500]	20.5 [27;1500]	23.4 [08;1500]	25.7 [31;1630]
Minimum [extreme]	-.9 [15;0700]	-4.8 [09;0700]	-9.1 [11;0600]	-8.4 [21;0700]	-5.2 [28;0600]	-3.5 [01;0600]
Relative humidity (percent)						
Monthly average	NA	NA	NA	NA	42.6 (22 days)	44.1 (29 days)
Maximum daily average	NA	NA	NA	NA	88.2 [25]	91.2 [03]
Minimum daily average	NA	NA	NA	NA	25.1 [19]	18.5 [29]
Maximum [extreme]	NA	NA	NA	NA	98.1 [25;0800]	95.1 [06;0530]
Minimum [extreme]	NA	NA	NA	NA	13.1 [08;1500]	11.9 [31;1630]
Total precipitation (mm)						
Monthly Total	9	98	22	120	7	106

Table 1. Characterization of microclimate at Ash Meadows, Nev., a desert site with a ground-water contribution to evapotranspiration, October 1986-September 1987—Continued

	April	May	June	July	August	September
			Solar radiation (W/m^2)			
Monthly average	442.6 (29 days)	454.6 (30 days)	421.8 (30 days)	503.0 (30 days)	488.6 (30 days)	410.8 (28 days)
Maximum daily average	523.5 [22]	539.4 [31]	563.8 [30]	574.2 [03]	525.0 [01]	473.9 [26]
Minimum daily average	189.3 [04]	264.0 [08]	207.8 [06]	90.4 [20]	409.3 [30]	355.3 [12]
			Net radiation (W/m^2)			
Monthly average	233.1 (29 days)	261.0 (30 days)	202.6 (30 days)	303.2 (30 days)	250.4 (30 days)	187.5 (28 days)
			Soil-heat flux (W/m^2)			
Monthly average	13.8 (29 days)	0.4 (30 days)	8.2 (30 days)	5.2 (30 days)	6.1 (30 days)	2.8 (26 days)
Maximum daily average	32.5 [19]	8.6 [27]	10.9 [02]	9.8 [26]	10.7 [02]	7.3 [01]
Minimum daily average	-.1 [05]	-7.5 [04]	5.1 [15]	-3.6 [20]	3.0 [24]	-.7 [30]
			Horizontal windspeed (m/s)			
Monthly average	2.3 (29 days)	2.4 (30 days)	1.9 (30 days)	2.6 (30 days)	1.8 (31 days)	0.8 (28 days)
Maximum daily average	9.4 [03]	4.8 [19]	5.4 [15]	8.8 [17]	5.1 [14]	2.4 [12]
Minimum daily average	.3 [15]	1.6 [21]	.7 [24]	.3 [13]	.5 [16]	.0 [16]
Maximum [extreme]	17.4 [03;1230]	9.4 [07;1930]	8.8 [15;1130]	13.0 [17;0730]	8.4 [14;1400]	8.0 [23;1630]
			Wind direction			
Azimuth of maximum speed	SW	NE	SW	SW	SW	SW
Percent time from:						
NE quadrant	16	11	9	1	1	11
SE quadrant	19	15	22	4	2	6
SW quadrant	36	37	52	62	92	49
NW quadrant	29	37	17	33	4	34
			Air temperature at 1.0 m (°C)			
Monthly average	18.8 (29 days)	21.7 (30 days)	27.6 (30 days)	27.7 (31 days)	29.0 (31 days)	24.9 (28 days)
Maximum daily average	24.1 [27]	26.3 [31]	31.0 [25]	32.0 [15]	31.7 [08]	31.0 [02]
Minimum daily average	10.6 [04]	16.6 [26]	20.9 [06]	18.1 [20]	23.5 [15]	21.8 [13]
Maximum [extreme]	35.0 [16;1430]	35.1 [06;1600]	41.1 [27;1500]	41.9 [14;1500]	41.0 [03;1400]	39.1 [01;1400]
Minimum [extreme]	.1 [04;0600]	6.4 [02;0300]	10.2 [07;0430]	11.8 [23;0500]	9.0 [25;0530]	8.2 [30;0600]
			Relative humidity (percent)			
Monthly average	29.0 (29 days)	30.2 (31 days)	16.7 (30 days)	17.9 (31 days)	15.6 (31 days)	15.8 (28 days)
Maximum daily average	72.3 [04]	90.8 [16]	62.5 [06]	57.8 [20]	22.2 [15]	32.1 [23]
Minimum daily average	15.1 [21]	13.9 [06]	10.7 [14]	11.1 [15]	10.1 [10]	12.1 [02]
Maximum [extreme]	95.7 [05;0500]	91.7 [16;0530]	91.5 [07;0430]	90.1 [20;1730]	49.5 [04;0600]	81.4 [23;2130]
Minimum [extreme]	8.5 [16;1430]	9.3 [31;1530]	<7.1 [13;1600]	<6.2 [14;1500]	<6.5 [31;1530]	<7.1 [20;0430]
			Total precipitation (mm)			
Monthly total	36	20	26	79	28	2

Table 2. Characterization of microclimate at northwest Las Vegas Valley, Nev., a desert site without a ground-water contribution to evapotranspiration, October 1986-September 1987

[Abbreviations: W/m^2, watt per square meter; m/s, meter per second; °C, degree Celsius; m, meter; mm, millimeter; NA, not available; SW, southwest; NW, northwest; NE, northeast; SE, southeast; <, less than. For monthly averages, number of days of record is indicated within parentheses; for maximum and minimum daily averages, day of month is indicated within brackets; for maximum and minimum extremes, day of month and hour of day are indicated within brackets]

	October	November	December	January	February	March
Solar radiation (W/m^2)						
Monthly average	186.1 (21 days)	138.2 (28 days)	100.9 (29 days)	123.6 (31 days)	215.8 (28 days)	309.2 (31 days)
Maximum daily average	233.2 [04]	174.0 [04]	135.7 [03]	163.8 [31]	317.3 [27]	415.8 [30]
Minimum daily average	151.1 [28]	47.9 [18]	33.5 [15]	37.0 [07]	56.3 [02]	133.9 [06]
Net radiation (W/m^2)						
Monthly average	NA	NA	NA	NA	NA	210.7 (31 days)
Soil-heat flux (W/m^2)						
Monthly average	4.5 (16 days)	-1.8 (29 days)	-0.9 (28 days)	0.5 (31 days)	3.5 (28 days)	3.2 (31 days)
Maximum daily average	11.0 [13.6]	7.1 [11]	6.8 [19]	13.0 [26]	11.9 [28]	16.6 [13]
Minimum daily average	-8.3 [16]	-13.7 [07]	-7.5 [07]	-12.6 [16]	-9.2 [25]	-17.1 [29]
Horizontal windspeed (m/s)						
Monthly average	2.6 (21 days)	2.84 (29 days)	2.2 (31 days)	3.1 (31 days)	2.7 (28 days)	0.6 (31 days)
Maximum daily average	4.7 [31]	4.8 [06]	4.1 [08]	5.0 [17]	4.9 [15]	1.0 [27]
Minimum daily average	1.4 [24]	1.3 [20]	1.3 [26]	1.3 [12]	.8 [11]	.2 [08]
Maximum [extreme]	7.5 [17;1200]	10.5 [29;1400]	6.6 [08;1100]	8.2 [28;0700]	8.2 [15;2100]	5.0 [04;0830]
Wind direction						
Azimuth of maximum speed	SE	NW	NW	SE	NW	NE
Percent time from:						
NE quadrant	3	12	1	2	4	8
SE quadrant	21	14	12	16	22	31
SW quadrant	11	7	7	8	9	7
NW quadrant	65	77	79	74	65	54
Air temperature at 1.0 m (°C)						
Monthly average	14.5 (21 days)	9.6 (28 days)	4.1 (31 days)	4.0 (31 days)	6.8 (28 days)	9.7 (31 days)
Maximum daily average	18.7 [29]	14.4 [03]	7.9 [05]	13.4 [28]	11.8 [10]	15.2 [13]
Minimum daily average	10.1 [20]	5.1 [09]	.8 [11]	-2.9 [16]	.6 [25]	5.6 [19]
Maximum [extreme]	27.0 [25;1600]	23.8 [03;1600]	17.6 [03;1500]	16.9 [26]	19.9 [06;1400]	23.5 [03;1600]
Minimum [extreme]	3.3 [21;0700]	-3.3 [09;0400]	-7.9 [11;0100]	-7.4 [0600]	-4.8 [23;0400]	-5.8 [30;0600]
Relative humidity (percent)						
Monthly average	NA	NA	NA	NA	45.6 (23 days)	42.0 (31 days)
Maximum daily average	NA	NA	NA	NA	91.0 [25]	81.8 [07]
Minimum daily average	NA	NA	NA	NA	23.2 [08]	20.5 [30]
Maximum [extreme]	NA	NA	NA	NA	93.5 [24;0700]	92.2 [01;0400]
Minimum [extreme]	NA	NA	NA	NA	14.9 [08;1500]	13.3 [31;1600]
Total precipitation (mm)						
Monthly total	23	80	51	42	54	69

Table 2. Characterization of microclimate at northwest Las Vegas Valley, Nev., a desert site without a ground-water contribution to evapotranspiration, October 1986-September 1987—Continued

	April	May	June	July	August	September
Solar radiation (W/m²)						
Monthly average	408.4 (30 days)	424.7 (28 days)	475.1 (30 days)	457.2 (31 days)	417.4 (30 days)	342.8 (30 days)
Maximum daily average	476.0 [22]	507.6 [31]	531.3 [17]	536.3 [03]	457.7 [18]	401.5 [07]
Minimum daily average	219.4 [29]	214.7 [15]	200.4 [06]	175.5 [20]	310.6 [20]	167.1 [13]
Net radiation (W/m²)						
Monthly average	183.6 (23 days)	189.7 (29 days)	196.9 (30 days)	202.3 (31 days)	162.8 (30 days)	99.7 (30 days)
Soil-heat flux (W/m²)						
Monthly average	4.8 (30 days)	16.9 (28 days)	16.0 (30 days)	11.6 (31 days)	8.4 (28 days)	2.1 (30 days)
Maximum daily average	25.5 [30]	29.8 [12]	33.3 [08]	26.9 [22]	16.0 [01]	10.0 [01]
Minimum daily average	-50.6 [05]	-1.4 [28]	-6.1 [06]	-15.6 [16]	1.7 [16]	-7.3 [13]
Horizontal windspeed (m/s)						
Monthly average	2.5 (30 days)	2.6 (31 days)	2.6 (30 days)	3.3 (31 days)	2.7 (29 days)	2.0 (30 days)
Maximum daily average	7.2 [18]	4.8 [20]	4.5 [15]	7.7 [17]	4.2 [08]	4.3 [05]
Minimum daily average	1.0 [04]	.7 [16]	1.3 [12]	1.7 [06]	1.4 [28]	1.3 [16]
Maximum [extreme]	8.5 [03;1200]	8.6 [01;1000]	9.4 [14;1330]	11.1 [17;1600]	8.1 [20;0730]	7.3 [01;1900]
Wind direction						
Azimuth of maximum speed	SE	SE	SE	SW	NE	SE
Percent time from:						
NE quadrant	5	4	3	6	4	5
SE quadrant	41	26	53	54	56	38
SW quadrant	11	37	10	17	18	12
NW quadrant	43	33	34	23	22	45
Air temperature at 1.0 m (°C)						
Monthly average	17.0 (30 days)	20.4 (30 days)	26.5 (30 days)	27.0 (30 days)	28.1 (30 days)	23.3 (30 days)
Maximum daily average	23.2 [27]	26.1 [14]	31.2 [27]	32.4 [14]	30.4 [05]	29.9 [01]
Minimum daily average	9.0 [04]	15.6 [26]	19.6 [06]	20.6 [07]	23.6 [16]	18.2 [13]
Maximum [extreme]	32.4 [27;1500]	34.1 [14;1200]	40.1 [27;1430]	41.5 [14;1530]	40.2 [08;1530]	37.5 [01;1300]
Minimum [extreme]	2.1 [21;0530]	6.9 [29;0130]	9.7 [17;0500]	9.5 [07;0500]	10.6 [25;0500]	9.2 [14;0500]
Relative humidity (percent)						
Monthly average	28.0 (30 days)	31.7 (31 days)	18.3 (30 days)	16.9 (30 days)	16.7 (30 days)	17.2 (30 days)
Maximum daily average	77.5 [04]	85.5 [16]	69.8 [06]	43.4 [21]	27.1 [07]	35.3 [23]
Minimum daily average	13.5 [18]	12.8 [06]	10.3 [26]	9.6 [14]	10.7 [01]	10.9 [01]
Maximum [extreme]	90.7 [04;0500]	88.8 [16;0130]	88.2 [07;0530]	84.8 [16;2130]	45.8 [02;0530]	67.0 [23;0500]
Minimum [extreme]	9.6 [16;1430]	9.0 [06;1600]	<6.8 [27;1430]	6.2 [14;1530]	7.1 [01;1530]	7.6 [01;1230]
Total precipitation (mm)						
Monthly total	77	124	27	56	0	0

The peak vapor-pressure deficit—the difference between the saturated vapor pressure and actual vapor pressure—normally coincided with the maximum daytime temperature and minimum relative humidity 2 to 4 hours after the maximum net radiation. Maximum net radiation occurred at solar noon; maximum summer temperatures and minimum relative humidity normally occurred at about 1500 hours, a time when persistent afternoon winds helped to increase surface drying.

The predominant afternoon wind direction was from the southwest during spring through autumn and from the northwest during the winter. At the northwest Las Vegas Valley site, southwest winds were deflected off the Sheep Range and recorded by the instruments as coming from the southeast.

Evapotranspiration

Energy Fluxes

The net transfer of energy into and out of the microclimates at both sites can best be seen by plotting the four major components of the energy-budget equation. The energy-flux distribution at the two sites for representative days in April, June, and August 1987 is shown in figures 2, 3, and 4. The total net radiation available at any given time is plotted against its component fluxes of soil-heat flux, sensible-heat flux, and latent-heat flux.

The relations among the three component fluxes change with the growing season of the plants at each site. At the Ash Meadows site, the April 1987 plot (fig. 2) shows the sensible-heat flux to be much greater than the latent-heat flux. As the plant growth increases in June, so does the latent-heat-flux component, at the expense of the sensible-heat flux (fig. 3). By August, the plant growth slows and the two fluxes are more equal (fig. 4). Although no data are available for the winter months, the ratio of latent- to sensible-heat flux would be at its minimum while the plants are dormant and while only soil moisture contributes to vapor discharge.

In addition, the flux distribution is different at the two sites because of the presence or absence of available ground water to support plant growth and vapor discharge. At the northwest Las Vegas Valley site, no ground-water component is available to maintain plant growth and, therefore, the few plants do not totally shade the soil. For this reason, the soil-heat-flux component is greater than that at the Ash Meadows site. With an absence of ground-water discharge at the northwest Las Vegas Valley site, plant growth and vapor discharge peaks in spring, so the ratio of the latent- to sensible-heat flux reaches its maximum for the year in spring, although the sensible-heat flux continues to dominate the energy use (fig. 2). By June, plants at the northwest Las Vegas Valley site are under severe stress as their root-zone soil moisture is depleted; they reach their wilt potential and become dormant (fig. 3).

The effects of cloud cover and rainstorms alter the normal shape of the plotted flux distributions. For example, clouds passing over the northwest Las Vegas Valley site altered the normal distribution of the flux curves (fig. 3). Spring and summer rainstorms generally increase the ratio of latent-heat to sensible-heat flux, and lower the soil-heat-flux curve, generally for less than 1 day after the precipitation ends.

Water-Vapor Losses

As previously discussed, three methods of monitoring *ET* were used. The eddy-correlation method is the most direct method of measuring actual *ET*, relying on direct and instantaneous measurements of vapor density and vertical windspeed. The latent-heat-flux residual method relies on not only the direct and instantaneous measurements of air temperature and vertical windspeed, but also the measurement of soil-heat flux and net radiation, to compute actual *ET*. The Penman-combination method calculates the potential *ET* by using the soil-heat flux and net radiation along with an empirical wind function, water-vapor changes, and other derived parameters and simplifying assumptions. The potential *ET*, therefore, is only a reference value that assumes a dense, well-watered crop canopy where the heat-exchange surface is the vapor-exchange surface. It does not take into account the effects of drying and the separation of the heat- and vapor-exchange surfaces. (The Penman-Monteith equation does take into account drying effects, but the equipment used for this study did not permit the direct measurement of the vapor-transport resistance without using latent- and sensible-heat flux residuals obtained by other methods.)

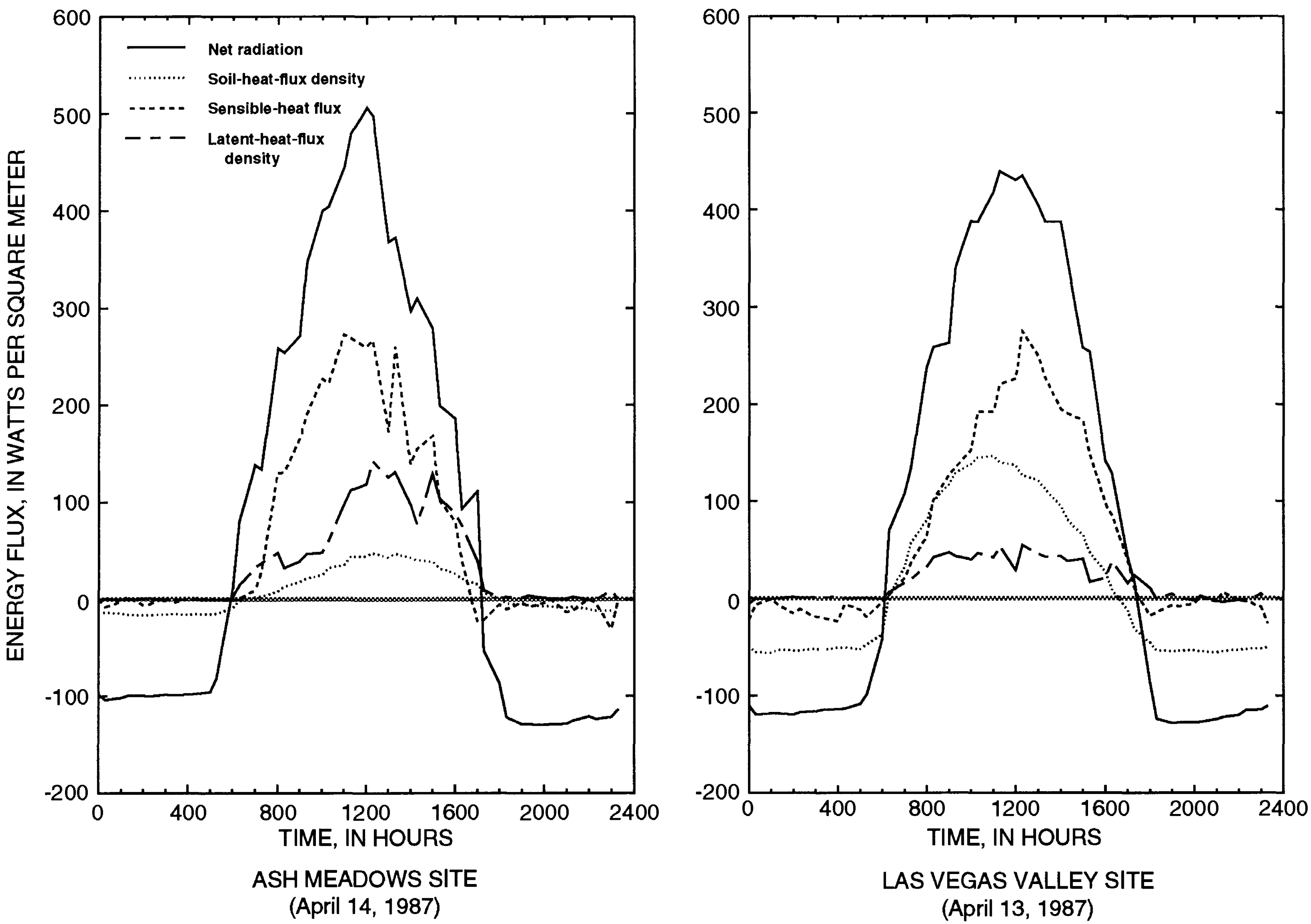

Figure 2. Energy-flux distribution at Ash Meadows and northwest Las Vegas Valley, Nev., sites for representative 24-hour period in April 1987.

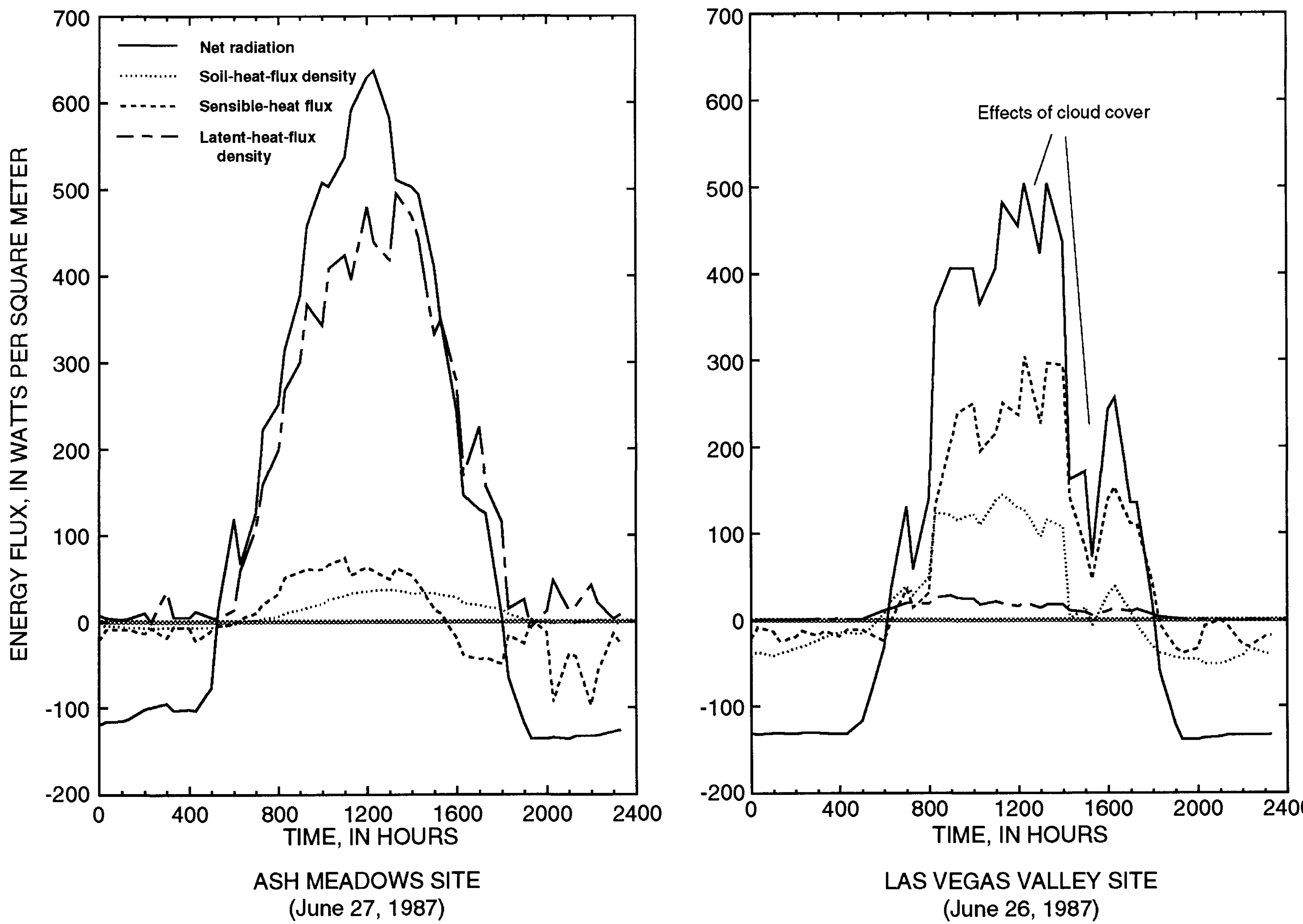

Figure 3. Energy-flux distribution at Ash Meadows and northwest Las Vegas Valley, Nev., sites for representative 24-hour period in June 1987.

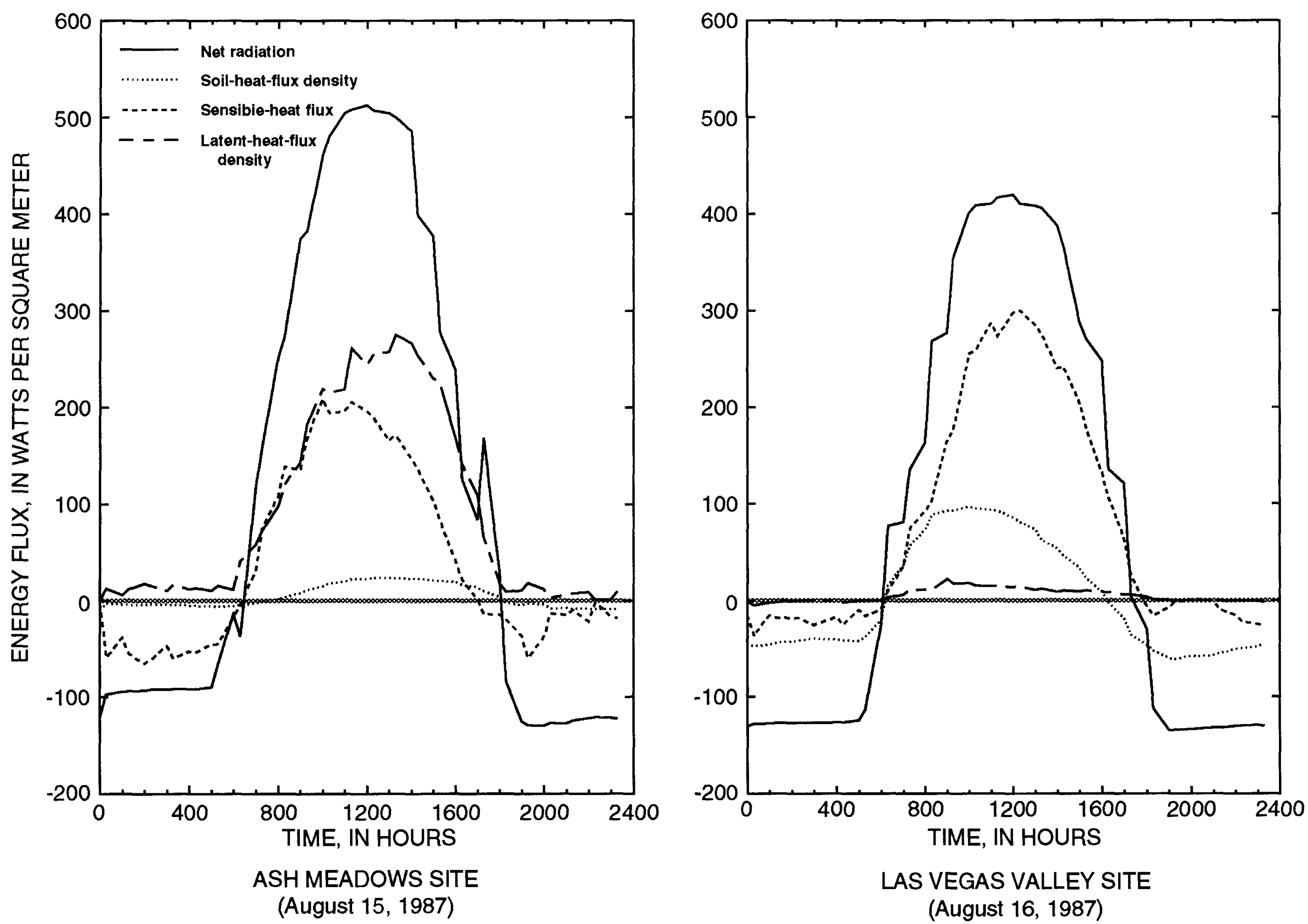

Figure 4. Energy-flux distribution at Ash Meadows and northwest Las Vegas Valley, Nev., sites for representative 24-hour period in August 1987.

Table 3. Average daily evapotranspiration rates by month at Ash Meadows and northwest Las Vegas Valley, Nev., sites, April-September 1987

[Values in millimeters per day (range of values in parentheses). Abbreviations: ET, evapotranspiration; eddy, eddy-correlation method; residual, latent-heat-flux residual method; Penman, Penman-combination method]

Month	Ash Meadows (site with ground-water contribution)			Northwest Las Vegas Valley (site without ground-water contribution)		
	Measured *ET* (eddy)	Calculated *ET* (residual)	Potential *ET* (Penman)	Measured *ET* (eddy)	Calculated *ET* (residual)	Potential *ET* (Penman)
April	1.4 (1.0-1.4)	1.9 (1.3-2.1)	5.4 (4.4-7.7)	0.6 (0.5-0.6)	0.8 (0.6-1.0)	6.1 (4.0-7.0)
May	1.4 (1.1-1.7)	2.0 (1.6-2.5)	7.2 (5.6-8.8)	.4 (0.3-2.0)	1.1 (0.8-1.5)	7.8 (1.1-13.0)
June	5.0 (2.6-6.3)	4.9 (2.8-5.7)	8.7 (4.1-12.8)	.3 (0.2-0.4)	1.0 (0.5-1.6)	10.2 (5.8-14.2)
July	5.0 (2.5-5.7)	4.8 (2.6-5.6)	9.0 (2.9-20.5)	.3 (0.2-0.4)	1.0 (0.5-1.6)	10.3 (5.7-14.3)
August	3.8 (3.2-4.5)	3.9 (3.5-4.3)	10.6 (6.0-20.5)	.2 (0.1-0.2)	.8 (0.3-1.2)	8.2 (2.8-12.0)
September	2.4 (2.0-2.8)	2.6 (2.0-2.8)	3.8 (3.1-4.4)	.0 (0.0-0.1)	.7 (0.4-0.9)	5.3 (4.2-6.9)

For each method, 30-minute estimates of *ET* were summed to give daily values of *ET*. Table 3 shows the average daily *ET* for each month using the eddy-correlation method and comparing it with calculated *ET* obtained from the latent-heat flux residual and with potential *ET* obtained from the Penman-combination equation.

The average daily *ET* rates (table 3) at both sites follow the same seasonal trend, as previously discussed and shown in the energy-flux plots (figs. 2-4). At Ash Meadows, where there is a ground-water contribution to *ET*, the *ET* rates are higher and peak during maximum plant-growth periods in early and mid-summer. At the northwest Las Vegas Valley site, where there is no ground-water contribution to vapor discharge, *ET* rates are lower and decrease with the onset of the drier part of the year.

Comparison of the three methods of obtaining *ET* indicates that the 30-minute measured *ET* values at Ash Meadows were fairly close to the calculated *ET* values obtained from the latent-heat-residual values, giving close daily averages for the two methods. At the northwest Las Vegas Valley site, the 30-minute differences between the two were greater, giving a less satisfactory result. This may have been partly due to the lower range of values being monitored, and to the inherent error introduced by the early-model Fritchen net radiometers used during this study. Measured *ET* never reached potential *ET* at either site.

Precipitation and wind affected the 30-minute and individual daily values. After a substantial rainstorm of generally 5 to 10 mm at the northwest Las Vegas Valley site, *ET* typically exceeds 1.5 mm/d and then drops back to nearly pre-storm levels in 2 to 3 days in the spring, or less than 1 day in the summer. In table 3, the average daily *ET* rates for each month do not include individual days with increased daily *ET* rates that were caused by high evaporation after precipitation. However, the range of values shown in table 3 does include some daily *ET* rates that show part of the effects of these storms. The range of values does not always reflect maximum *ET* rates immediately after a rain storm, when instruments are recovering from the effects of the storm. For example, after an unusually intense thunderstorm at the northwest Las Vegas Valley site in mid-May, recording 114 mm of precipitation with significant local runoff and flooding, the *ET* instrumentation was inoperative during the post-storm period. This storm increased *ET* rates above pre-storm levels for more than a week.

On days with increased wind, the potential *ET* values calculated within the Penman-combination method were considerably higher than either the measured (eddy) or calculated (residual) *ET* values. This potential *ET* could be reached only under ideal conditions, with adequate moisture in the soils and adequate water within the plants to meet the vapor demand without surface drying effects. For example, at the Ash Meadows site on August 14, 1987, the potential *ET* for the day was 20.4 mm/d, compared with a measured *ET* of 3.2 mm/d and a calculated (residual) *ET* of 3.5 mm/d. One day later, under similar climatic conditions, except for windspeed that dropped from a daily average of 5 to 1 m/s, the potential *ET* for the day was 7.0 mm/d, compared with a measured *ET* of 3.2 mm/d and a calculated (residual) *ET* of 3.5 mm/d. This change of potential *ET* from 20.4 to 7.0 mm/d (while the measured *ET* changed less than 0.1 mm/d) indicates the limitations in using the Penman-combination method to estimate *ET* without considering changes in the vapor-exchange surface and its relation to the heat-exchange surface. However, when surface differences are considered, the potential *ET* values are more probable for the *ET* site under consideration. Using the 30-minute latent- and sensible-heat fluxes on both days to calculate the vapor-transport resistance, then using this resistance and the sensible-heat transport resistance, the thermodynamic psychrometer constant can be replaced by the apparent psychrometer constant in the Penman-combination equation for each of the 30-minute potential *ET* calculations for both days. The daily total for both days then becomes approximately equal to the actual *ET* of 3.2 mm/d. Thus, the potential *ET* using the thermodynamic psychrometer constant, as shown in table 3, should be viewed as a maximum value under ideal conditions that do not exist and cannot be achieved at either site.

During periods when weather conditions were fairly consistent, the calculated vapor-transport resistance gave fairly consistent values at the Ash Meadows site. These values could be used in the Penman-Monteith equation on days when direct measurements of latent-heat flux were not available.

Evapotranspiration Measurements at Two Sites in the Mojave Desert of Southern Nevada

From the data collected in this study and work previously completed at the Franklin Lake playa in California (Czarnecki and Stannard, 1986; Czarnecki, 1987), 15 km southwest of Ash Meadows, some preliminary observations can be made about evapotranspiration rates in the Mojave Desert region of southern Nevada, in areas with and without ground-water contributions to vapor discharge:

1. At the northwest Las Vegas Valley site where the water table is deep and the land is covered with either sparse vegetation or bare soil, *ET* was greatest in early spring, but was less than 0.6 mm/d. As summer progressed and soil moisture was depleted, *ET* dropped below 0.1 mm/d and vegetation ground cover wilted and dried. After substantial rainstorms from 5 to 10 mm, *ET* exceeded 1.5 mm/d and then dropped to pre-storm levels in 2 to 3 days in the spring, and in less than 1 day in summer.

2. At the Ash Meadows site where the water table is shallow (less than 2.5 m) and the understory is dense and soils are moist, *ET* increased with solar radiation and plant growth, from 1 mm/d in winter to an average of 1.5 to 3.0 mm/d in spring. The highest average of about 5.0 mm/d (with fluctuations between 3.0 and 7.0 mm/d) was in June, July, and early August. *ET* then dropped from 3.0 to less than 1.0 mm/d by late autumn. In contrast, at Franklin Lake Playa where the water table is shallow and the land is covered with either sparse vegetation or bare soil, the *ET* ranged from less than 1 mm/d in winter to 2 mm/d in spring, and about 1.5 mm/d in summer.

Ground-Water Discharge by Evapotranspiration

The presence or absence of a ground-water contribution to *ET* at both sites was supported by the depth to ground water and the use of a neutron soil-moisture probe to measure monthly changes in the soil moisture with depth. At Ash Meadows, the depth to the water table below land surface fluctuated from 2.6 m in October 1986 to 0.9 m in March 1987, while at the northwest Las Vegas Valley site, the water level remained fairly stable throughout the year at 8.4 m. Throughout the year, the volumetric water content of the soil at the Ash Meadows site tended to increase with depth, reaching 0.46 g/cm^3, or a 25-percent moisture content by mass, just above the water table. The upward decrease in moisture content at Ash Meadows throughout the year indicates a net upward movement of moisture from the water table to the surface. In contrast, the soil column at the northwest Las Vegas Valley site tended to be drier with depth and to remain that way throughout the year. The 14.7-percent soil-moisture content at a depth of 0.5 m dropped to less than 9.8 percent at 4.0 m—the bottom of the neutron-access tube. Except for minor perturbations in the upper 0.5 m of the soil column caused by precipitation, the soil-moisture content at any depth remained fairly constant at the Las Vegas Valley site during the study. This decrease in soil moisture with depth indicates an absence of any measurable upward movement of water in the unsaturated zone from ground water at the Las Vegas Valley site.

By comparing the two sites used in this study, a general estimate of the ground-water contribution to *ET* can be made at a site in the Mojave Desert with ground water supporting *ET*. At each site, the daily *ET* total was adjusted, as necessary, to remove an infrequent (but significant) *ET* component due to precipitation. Short-term moisture losses from the soil came from precipitation-dampened soils, for which adjustments were made, or from ground-water discharge through the unsaturated zone, which is the quantity to be derived. Monthly *ET* totals (fig. 5) based on average daily rates (table 3) indicate that about 520 mm of ground water was lost to *ET* at Ash Meadows during the 6 months of record, April through September 1987. This is in general agreement with the range of estimates used by Walker and Eakin (1963, p. 23) for areas of native vegetation in the Amargosa Desert where the depth to water was between 0 and 1.5 m. Their estimated rates ranged from 320 to 760 mm/yr.

In addition to estimating amounts of *ET* supplied by ground water, field measurements of *ET* using the eddy-correlation method were applied to help delineate discharge areas in the vicinity of Corn Creek Springs, about 8 km southeast of the northwest Las Vegas Valley site. Measurements at several temporary sites near Corn Creek Springs were obtained during dry periods in the summer. Results indicate that the daily patterns of summer *ET* associated with areas where *ET* is supported primarily by ground water were limited to the area within 0.2 km north and 0.4 km southwest of Corn Creek Springs. This indicates the discharge area is smaller than that mapped by Winograd and Thordarson (1975, pl. 1), which extended more than 3 km north of Corn Creek Springs.

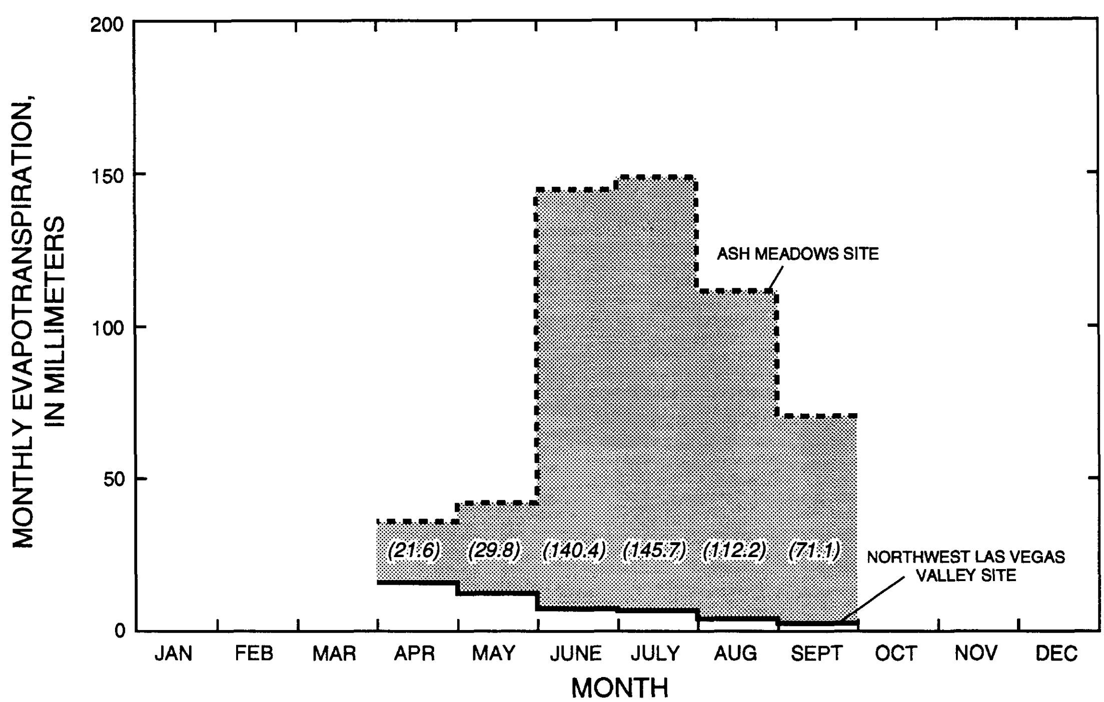

Figure 5. Estimated monthly evapotranspiration at Ash Meadows and northwest Las Vegas Valley, Nev., sites, April-September 1987. Difference (in parentheses) is approximate ground-water contribution to evapotranspiration; total for 6-month period is about 520 millimeters.

SUMMARY

The eddy-correlation method was used to make point measurements of actual evapotranspiration at two representative microclimate settings in the Mojave Desert of southern Nevada, one at Ash Meadows with a ground-water contribution to vapor discharge, and one at northwestern Las Vegas Valley without a ground-water contribution to vapor discharge. The rate and timing of actual *ET* at each site was evaluated to observe the effective difference in available water for vapor discharge between the two sites. This comparison indicates the importance of ground water in maintaining *ET* rates. As the soil-moisture content remained fairly constant during the study, the amount of *ET* due only to ground-water discharge can be inferred by comparing the rates of evapotranspiration at the two sites. By contrasting the difference in *ET* rates at other similar sites with and without ground water discharge, the quantified ground-water discharge around basin playas or springs can be quantified.

SUGGESTIONS FOR FUTURE STUDY

Further work could lead to quantification of actual ground-water discharge by evapotranspiration in the arid ground-water basins of the western United States. This work would include point measurements of actual *ET* at sites throughout a basin selected on the basis of satellite imagery mapping of vegetation and knowledge of depth to ground water and soil composition. These measurements would accurately quantify basinwide evaporative losses from the soil and vegetation, the major form of water discharge from desert basins in the western United States. Evaporative water discharge measured over an entire basin could then be compared with recharge estimates for the same basin. The results could be used to reduce the discrepancy between recharge and discharge estimates common for water budgets for arid basins.

Past estimates of discharge from basins in the arid parts of the western United States have typically relied on empirical methods or equations that generally used available weather data to estimate *ET*. These equations were originally derived for vapor losses over well-watered agricultural crops. The validity of these empirical equations to indirectly estimate *ET* in arid basins over native vegetation has yet to be thoroughly tested. The equations could be checked by taking point measurements of actual *ET* and comparing the results with the derived *ET* values obtained from the empirical equations. Such a comparison would identify those equations with the greatest potential for application within the western desert basins of the United States.

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