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

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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.

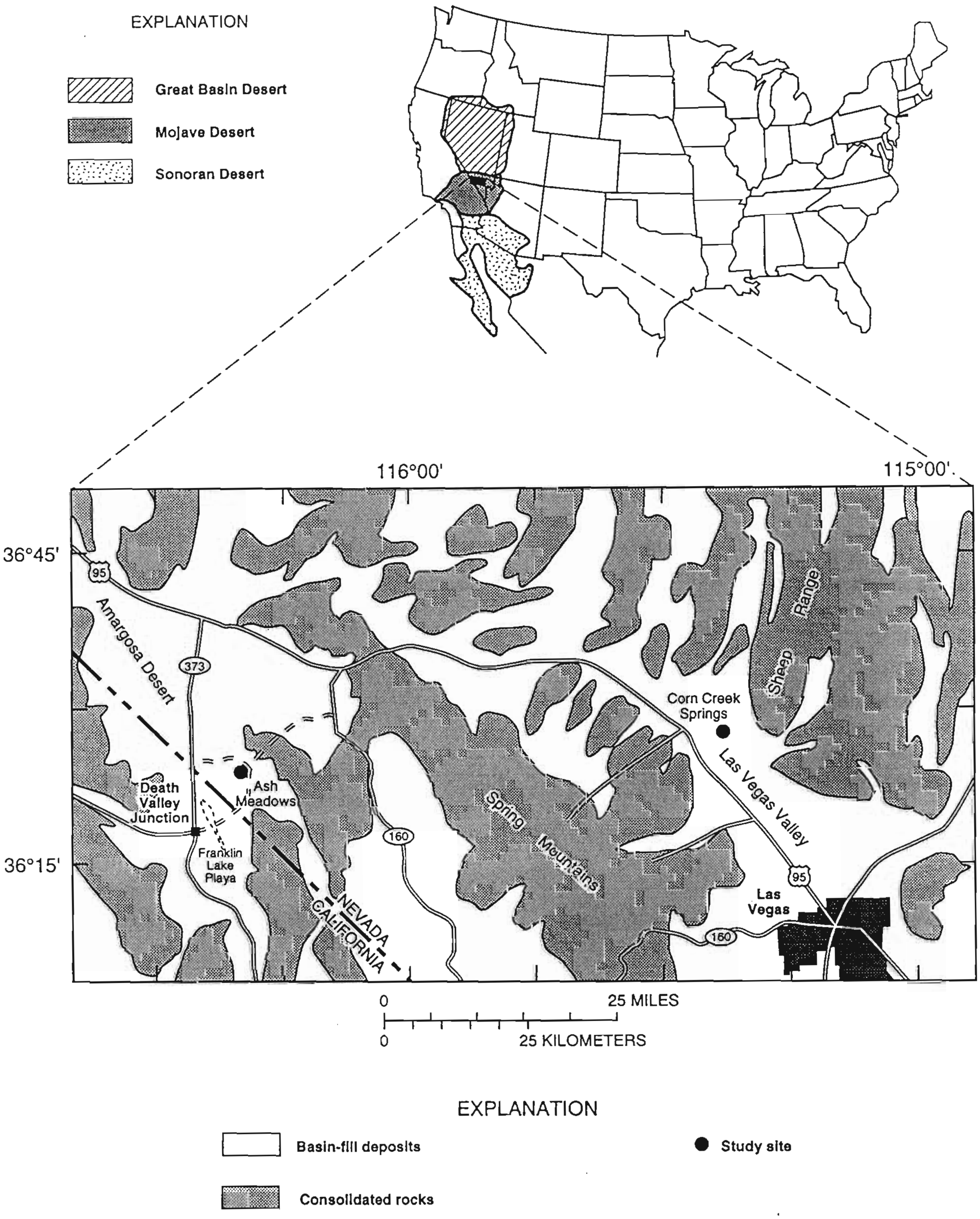


Figure 1. Evapotranspiration sites at Ash Meadows and northwest Las Vegas Valley. Desert areas modified from MacMahon (1985).

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):

$$\lambda E = \overline{V'W'}\lambda, \tag{2}$$

and

$$H = \overline{W'T'}\rho_a C_p, \tag{3}$$

where

$'$ is the instantaneous deviation from the mean
$\overline{}$ 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):

$$\text{EBC} = \frac{\lambda E + H}{R_n - G} \times 100 \tag{4}$$

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):

$$\alpha = \lambda E = R_n - G - H . \tag{5}$$

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:

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

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)

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.

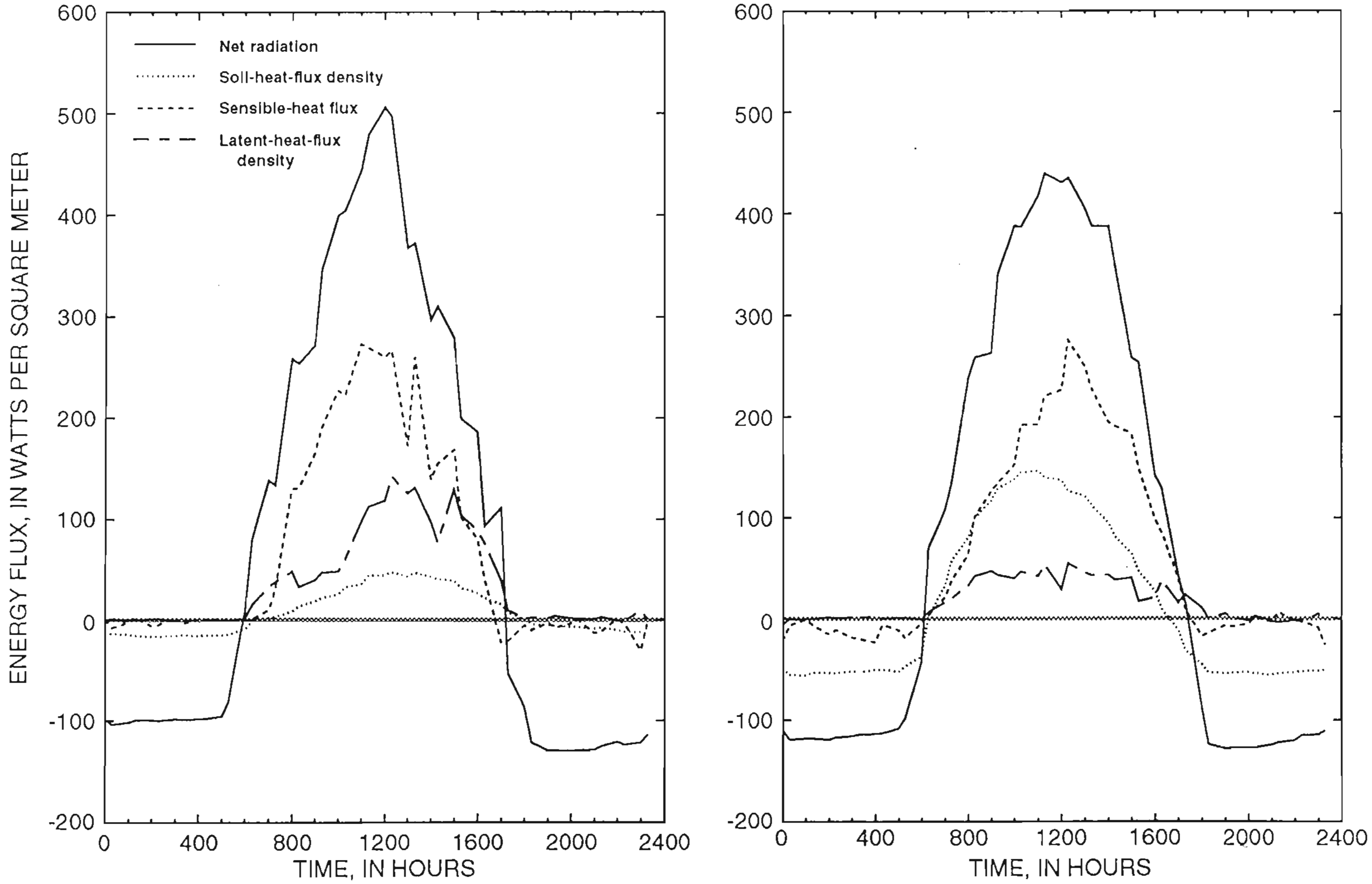
Total precipitation for the year of record was 553 mm at Ash Meadows and 603 mm at northwest Las Vegas Valley. The period was abnormally wet for an area where annual precipitation is commonly less than 127 mm. Major winter and spring Pacific storms supplied a regional source of unusually persistent "rain-band" 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—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—Continued

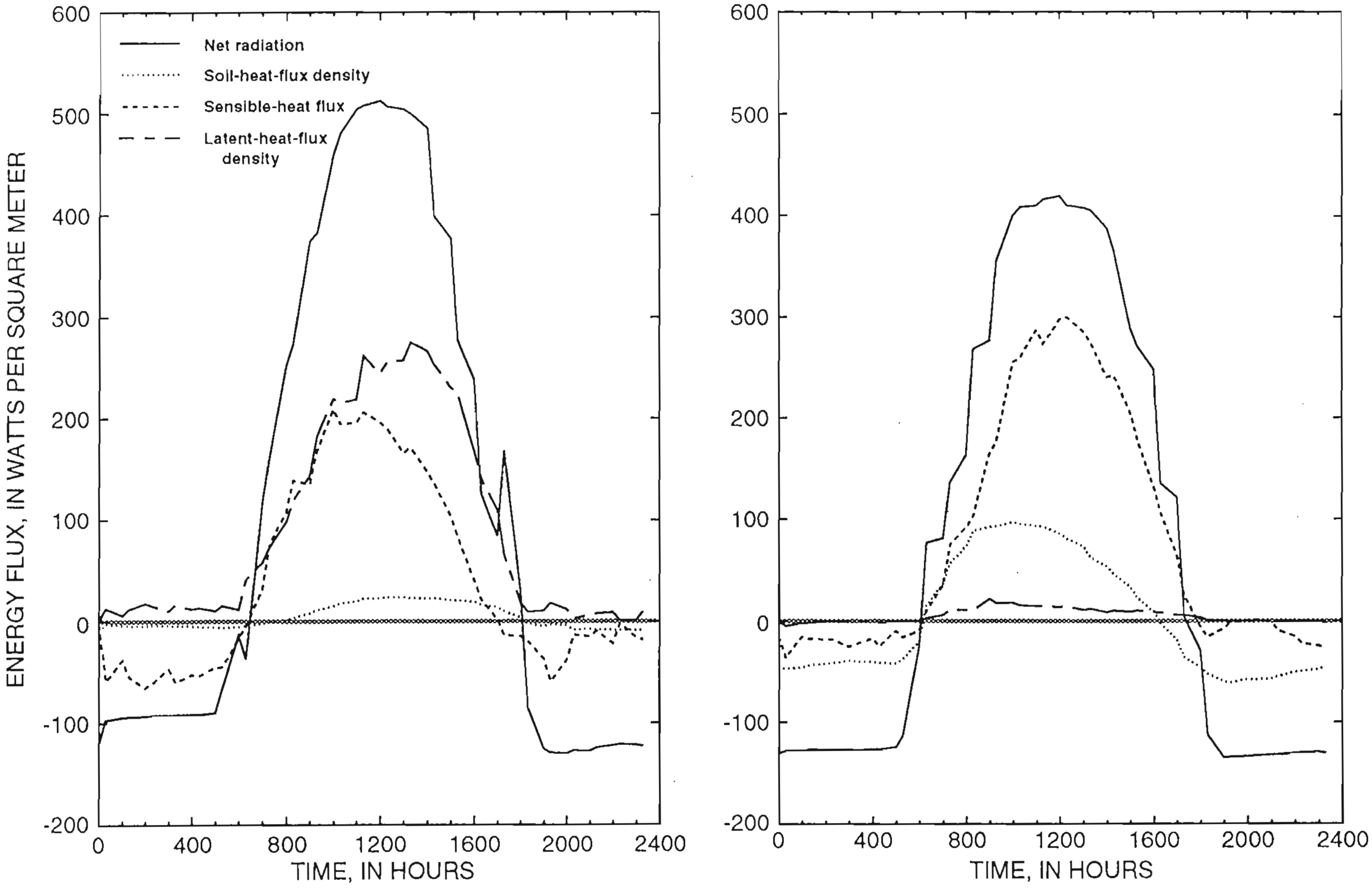
	April	May	June	July	August	September
			Solar radiation (W/m^2)			
Monthly average	408.4 (30 days)	424.7 (28 days)	475.1 (30 days)	457.2 (31 days)	417.4 (30 days)	342.8 (30 days)
Maximum daily average	476.0 [22]	507.6 [31]	531.3 [17]	536.3 [03]	457.7 [18]	401.5 [07]
Minimum daily average	219.4 [29]	214.7 [15]	200.4 [06]	175.5 [20]	310.6 [20]	167.1 [13]
			Net radiation (W/m^2)			
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/m^2)			
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



ASH MEADOWS SITE
(April 14, 1987)

LAS VEGAS VALLEY SITE
(April 13, 1987)

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



ASH MEADOWS SITE
(August 15, 1987)

LAS VEGAS VALLEY SITE
(August 16, 1987)

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

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

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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