Summer Evapotranspiration Rates, by Bowen-Ratio and Eddy-Correlation Methods, in Boulder Flat and in Maggie Creek Area, Eureka County, Nevada, 1991–92

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length, area, and volume		
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
Rate or velocity		
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
meter per second (m/s)	2.237	mile per hour
Density and mass		
kilogram (kg)	2.205	pound
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot
Energy, power, and energy flux		
joule (J)	0.0009479	British thermal unit
watt (W)	3.413	British thermal unit per hour
watt per square meter (W/m^2)	0.3170	British thermal unit per hour per square foot
Heat of vaporization		
joule per kilogram (J/kg)	0.0004303	British thermal unit per pound
Pressure		
kilopascal (kPa)	0.1450	pound-force per square inch

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

Summer Evapotranspiration Rates, by Bowen-Ratio and Eddy-Correlation Methods, in Boulder Flat and in Maggie Creek Area, Eureka County, Nevada, 1991–92

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Abstract

Evapotranspiration (ET) data were collected during the summers of 1991 and 1992 in the hydrographic areas known as Boulder Flat and the Maggie Creek Area, in the gold-mining region along the Carlin trend in Eureka County, Nev. Measurements were made in greasewood; in mixed communities of rabbitbrush, sagebrush, and greasewood; and in meadow grass. Two methods of monitoring ET were used in the study area: the Bowen-ratio method and the eddy-correlation method. Summertime daily ET rates ranged from 0.2 to 2.0 millimeters per day at two ET-monitoring sites in Boulder Flat and ranged from 0.7 to 4.8 millimeters per day at three sites in the Maggie Creek Area. Measurements were made during the fifth and sixth years of a continuing drought.

INTRODUCTION

Background

The Carlin trend is a northwestward structural alignment of gold deposits in north-central Nevada (Knutsen and Wilson, 1990). The Carlin trend north of the Humboldt River extends at least 70 km northwest of Carlin, Nev. Within this area are several mining operations (fig. 1). The area crosses six hydrographic areas (fig. 1), which have a combined extent of about 5,400 km^2, including several drainage subbasins of the Humboldt.

Pumpage of ground water in the mining and milling operations along this part of the Carlin trend is increasing and is expected to continue well into the next century. Several large open-pit gold mines extend below the water table. The pits therefore must be pumped continuously to extract large volumes of ground water during the dewatering phase of the mining operation. According to R.W. Plume (U.S. Geological Survey, oral commun., 1995), about 22 hm^3 (18,000 acre-ft) of ground water was pumped during mining and milling operations in 1990 and total pumpage in 1993 was about 140 hm^3 (110,000 acre-ft).

Potential long-term effects from mining operations include water-level declines over large areas, changes in streamflow of the Humboldt River and its tributaries, and changes in ground-water and surface-water quality. However, these potential effects cannot be assessed in the future unless existing hydrologic conditions are documented.

The collection of hydrologic data needed to document these conditions began in 1988 with a water-resources study of the Maggie Creek Area[1] (Plume, 1995). The work was done by the U.S. Geological Survey in cooperation with the Nevada Division of Water Resources. A larger study to document the hydrologic characteristics of the six hydrographic areas along the

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

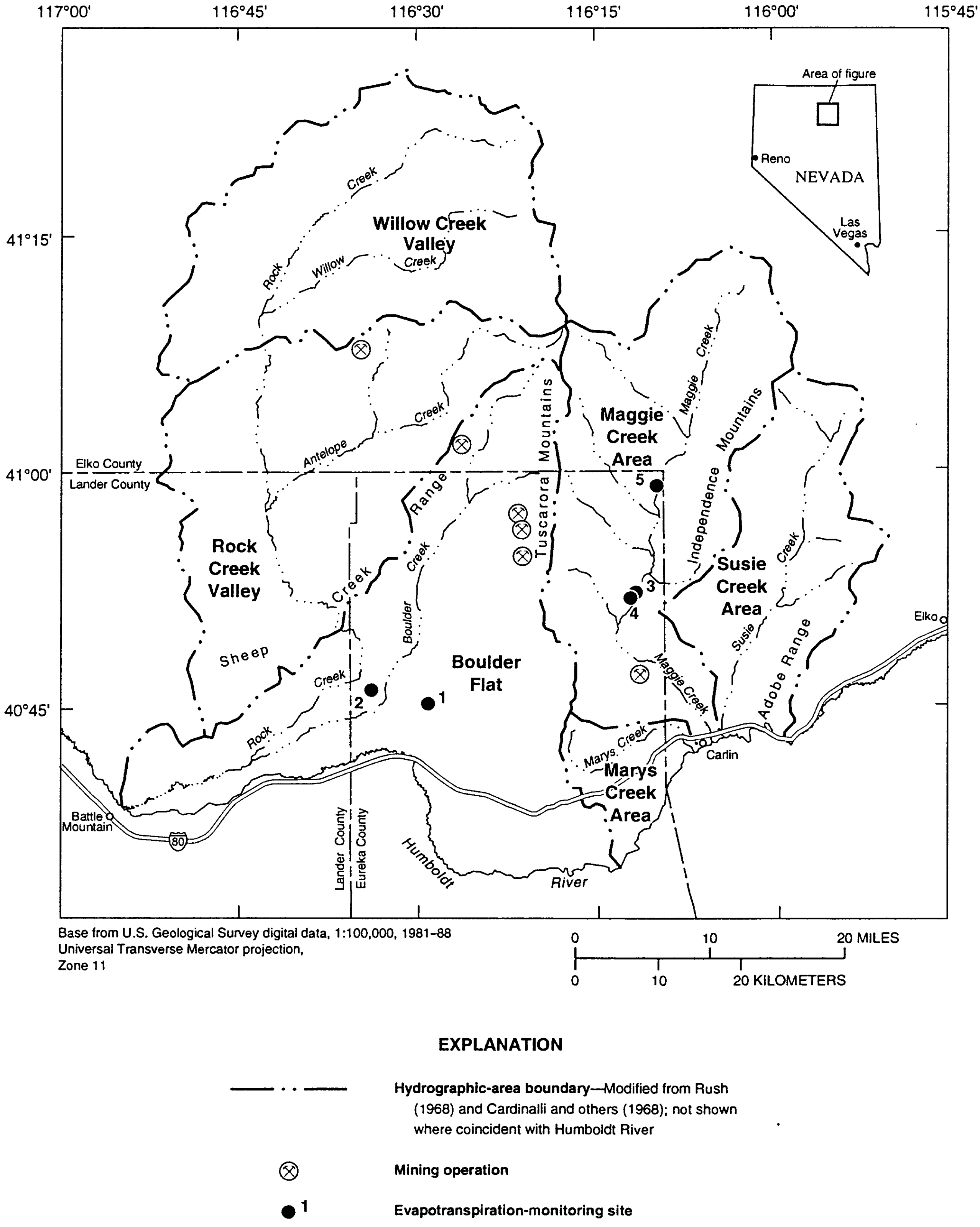

Figure 1. Evapotranspiration-monitoring sites in Boulder Flat and Maggie Creek Hydrographic Areas, north-central Nevada. Also shown are four other hydrographic areas in vicinity and local mining operations.

Carlin trend and to monitor hydrologic conditions during the dewatering phases of the mining operations was started in August 1990 by the U.S. Geological Survey in cooperation with the Nevada Department of Water Resources. Plume and Stone (1992) published interim results of that study.

Purpose and Scope

This report describes the results of a study to document water losses through evapotranspiration (ET) in selected vegetation communities along the Carlin trend during the two summers 1991 and 1992. Boulder Flat was chosen for its greasewood communities, and the Maggie Creek Area was selected for its rabbitbrush and meadow-grass communities.

Five ET-monitoring sites were chosen for this study (fig. 1, table 1). In 1991, the initial ET-data collection was limited to three sites: sites 1 and 2 in Boulder Flat, and site 3 in the Maggie Creek Area. Fieldwork in 1991 included 1 week of data collection at each site during July. On the basis of the first summer's results, site 1 and two additional sites (4 and 5) in the Maggie Creek Area were monitored during late June and early July of 1992. During this study, ET rates were estimated from micrometeorological data collected by the Bowen-ratio and eddy-correlation methods. (The micrometeorological data are on file at the U.S. Geological Survey, Carson City, Nev.)

Table 1. Description of five evapotranspiration-monitoring sites in Boulder Flat and in Maggie Creek Area, north-central Nevada

Site no.	Period of instrumentation [1]		Vegetation type	Altitude (meters)	Water table (meters below land surface)	Geographic location and relevant 7.5-minute U.S. Geological Survey topographic quadrangle
	Setup	Removal				
			Boulder Flat			
1	7/9/91 6/20/92	8/7/91 7/30/92	Greasewood	1,415	5.2–5.5	Lat 40°45′22″ N., long 116°29′03″ E. NW ¼NE ¼NE ¼ sec. 7, T. 33 N., R. 49 E. (Rodeo Creek SW quadrangle).
2	7/24/91	8/7/91	Sagebrush–greasewood (with some grasses and rabbitbrush).	1,408	5	Lat 40°46′14″ N., long 116°33′51″ E. NE ¼NW ¼NE ¼ sec. 4, T. 33 N., R. 48 E. (Sheep Creek Range SE quadrangle).
			Maggie Creek Area			
3	7/25/91	8/7/91	Rabbitbrush (with some grasses and sagebrush).	1,590	4	Lat 40°52′32″ N., long 116°11′37″ E. SE ¼NW ¼SW ¼ sec. 36, T. 35 N., R. 51 E. (Swales Mountain NW quadrangle).
4	6/20/92	7/7/92	Rabbitbrush (with some grasses and sagebrush).	1,588	3	Lat 40°52′18″ N., long 116°11′58″ E. SE ¼SE ¼SE ¼ sec. 35, T. 35 N., R. 51 E. (Schroeder Mountain quadrangle).
5	6/20/92	7/7/92	Meadow grass	1,653	1	Lat 40°59′23″ N., long 116°09′44″ E. SW ¼SE ¼SE ¼ sec. 19, T. 36 N., R. 52 E. (Swales Mountain NW quadrangle).

[1] Not necessarily coincident with period of data collection.

Description of Plant Communities and Evapotranspiration-Monitoring Sites

Vegetation on the valley floor within Boulder Flat consists mainly of mixed communities of greasewood, sagebrush, rabbitbrush, and grass. Large stands of greasewood predominate in the eastern part of the area, whereas mixed communities are present to the west along the channels of Boulder and Rock Creeks. In the Maggie Creek Area, the hillside vegetation is predominantly sagebrush, whereas rabbitbrush mixed with grasses and some sagebrush cover the alluvial channel deposits on the valley floor (except where natural grass meadows exist or where shrubs have been cleared for grazing). Dense willow communities and marshes extend into broad, green-grass meadows in and along the Maggie Creek channel.

Site 1 (fig. 1, table 1), is in a typical greasewood (*Sarcobatus*) community in the central part of Boulder Flat. The plant canopy generally is less than 0.5 m high, and ground cover was estimated to be 20 percent. During 1991–92, depth to ground water ranged from 5.2 to 5.5 m below the land surface in a well at the site.

Site 2 (fig. 1, table1), also in Boulder Flat (about 7 km west-northwest of site 1), is in a mixed community of sagebrush (*Artemisia*) and greasewood, with some interspersed rabbitbrush (*Chrysothamnus*) and grasses (*Gramineae* and *Agropyron* spp.) adjacent to the ephemeral Boulder Creek. This mixed plant community is typical of the western part of Boulder Flat where it has not been cleared by ranching activities. The average canopy height is 0.8 m, and ground cover was estimated to be 40 percent. Depth to ground water was estimated to be about 5 m at the site on the basis of water-level measurements in two wells, 2.1 km to the east and 2.5 km to the west of the site, respectively.

Sites 3 and 4 (fig. 1, table 1), in the Maggie Creek Area, are in rabbitbrush with some wild grasses and sagebrush. The sagebrush, although more predominant at site 3 than at site 4, constituted less than 15 percent of the plant community at both sites. The average canopy height at sites 3 and 4 is approximately 0.7 m, and ground cover exceeds 50 percent. Depth to ground water was estimated to be 4 m at site 3 and 3 m at site 4, on the basis of interpolation between the ground-water level in a monitoring well on the west edge of the alluvial channel deposits, west of both sites, and the water level in Maggie Creek, east of both sites. (According to R.W. Plume (U.S. Geological Survey, oral commun., 1993), the flow in Maggie Creek is ground-water discharge in this part of the drainage.)

Site 5 (fig. 1, table 1), in the Maggie Creek Area, is in a grassy meadow. Surface soils are moist and depth to water was estimated to be about 1 m. The average canopy height is 0.5 m, and the grasses form a thick green (100-percent) ground cover.

EVAPOTRANSPIRATION AS COMPONENT OF ENERGY BUDGET

Evapotranspiration is one of several energy-driven processes that compete for the available energy at or near the land surface. In an energy budget, the available energy from net radiation is partitioned into energy to drive the ET process of converting water from liquid to vapor (latent-heat flux), energy to warm the air by returning energy to the atmosphere as heat (sensible-heat flux), and energy to heat the soil by transferring part of the available energy to the soil (soil-heat flux):

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

where R_n is net radiation, in watts per square meter;

λ is latent heat of vaporization, equal to 2,450 joules per gram at 25°C;

E is quantity of water vaporized (water-vapor flux density), in grams per square meter per second;

H is sensible-heat flux, in watts per square meter; and

G is soil-heat flux, in watts per square meter.

Because other, minor, energy-consuming processes can be considered negligible, net radiation equals the sum of the three fluxes (eq. 1) and is the net difference between all upward and all downward long- and short-wave radiation fluxes.

The product λE (eq. 1), latent-heat flux (in watts per square meter), is needed to derive ET rates. The amount of available energy that is partitioned to ET as latent-heat flux depends on such factors as the season, time of day, cloud cover, soil properties, canopy cover, and available moisture. The maximum ET at a given site usually occurs midday in the summer months, which are characterized by maximum solar radiation and minimum cloud cover, provided that the moisture available in the soils and plants equals or exceeds the amount to be evaporated or transpired. Thus, maximum ET rates commonly occur in the summer in desert environments after convective storms and decline to prestorm rates during the next several days to weeks. Sustained ET typically occurs in late spring and early summer during maximum plant growth and as the soil is depleted of moisture from stored snowmelt and spring rains.

EVAPOTRANSPIRATION-MONITORING METHODS

To estimate ET, the amount of water-vapor transfer from both the ground surface and plants to the atmosphere is measured. The amount of water vapor both transpired by plants and evaporated from the soil is calculated from energy fluxes measured over short time intervals and accumulated to obtain daily totals. In this study, two methods were used to estimate ET during the plant's growing season: the Bowen-ratio method (Tanner, 1960; B.D. Tanner and J.P. Greene of Campbell Scientific, Inc., and G.E. Bingham of Utah State University, written commun., 1987) and the eddy-correlation method (Swinbank, 1951; Tanner and others, 1985). Both methods require field instruments that can measure the vertical transport of energy in the form of sensible- and latent-heat flux across an ET surface just above the plant canopy, generally a few meters above the land surface.

Bowen-Ratio Method

The Bowen-ratio method uses the ratio of the vertical air-temperature and vapor-pressure gradients across a given ET surface to determine the proportion of energy used as sensible-heat flux relative to latent-heat flux. Assuming that the eddy diffusivities for heat and vapor are equal, the Bowen ratio is the ratio of the sensible- to latent-heat flux (Brutsaert, 1982, p. 215):

$$\beta = \gamma \frac{\Delta T}{\Delta e} = \frac{H}{\lambda E}, \qquad (2)$$

where β is Bowen ratio (unitless);

γ is psychrometric constant (product of air pressure and specific heat of air divided by latent heat of vaporization and by ratio of molecular weight of water to dry air), in kilopascals per Kelvin;

ΔT is difference in air temperature, in Kelvins;

Δe is difference in vapor pressure, in Kilopascals;

H is sensible-heat flux, in watts per square meter;

λ is latent heat of vaporization, equal to 2,450 joules per gram at 25°C; and

E is quantity of water vaporized (water-vapor flux density), in grams per square meter per second.

In calculations by the Bowen-ratio method, the energy needed to heat the soil (soil-heat flux G) is removed from the total available energy (net radiation R_n) and the remaining net energy is apportioned between the sensible- and latent-heat flux by using the Bowen ratio (eq. 2). In the energy-budget equation (eq. 1), the soil-heat flux is subtracted from both sides of the equation and the remaining (net) energy is divided between the sensible- and latent-heat flux by using the Bowen ratio. The defined latent-heat flux (λE) is then divided by the latent heat of vaporization to obtain water-vapor flux density and, hence, equivalent evapotranspiration in millimeters of water per unit area per unit time.

In this study, the Bowen-ratio equipment was used to sample air alternately from two heights above the plant canopy. Air samples were taken at 0.75 m and 1.75 m above the canopy in 1991 and at 0.5 m and 1.5 m in 1992. A cooled-mirror hygrometer was used to measure the dew-point temperature, from which the vapor pressure can be obtained. Every 2 minutes the air was drawn through the cooled mirror, first at one height, then at the other. The mirror was allowed to stabilize on the new dew point for 40 seconds prior to making measurements for 80 seconds. The dew-point temperature was measured every second, and the average vapor pressure was obtained for the entire 2-minute interval. Every 4 minutes the average vapor pressure at each height was available to calculate a vapor-pressure gradient. A total of five vapor-pressure gradients were averaged to define the vapor-pressure gradient during each 20-minute interval of the day. Similarly, the air-temperature gradient was obtained by using chromel-constantan thermocouples (0.076 mm in diameter) to measure air temperature at the two heights. Net radiation was measured by using a Fritschen Q-6 net radiometer, and soil-heat flux was measured by using Thornthwaite soil-heat flux disks set 0.05 m below the soil surface. Changes in the energy stored in the soil layer above the soil-heat flux disks were obtained by periodically sampling the soil bulk density and soil water content and by continuously monitoring the average soil temperature. For a general description of the Bowen-ratio equipment, field procedures, and data acquisition, see Campbell Scientific, Inc. (1991).

Eddy-Correlation Method

The eddy-correlation method, first proposed by Swinbank (1951), provides the most direct means of measuring the actual water-vapor flux across the ET surface. In the eddy-correlation method, the turbulent components of latent- and sensible-heat fluxes can be calculated independently of the other four energy fluxes (eq. 1) by using selected field measurements. Latent-heat flux (λE) is calculated from the covariance of the measured vertical wind speed and vapor density, and sensible-heat flux (H) is calculated from the covariance of the measured vertical wind speed and air temperature. The eddy-correlation flux equations are

$$\lambda E = \lambda \overline{w'\rho_v'} \quad (3)$$

and

$$H = \overline{w'T_a'} \rho_a C_p, \quad (4)$$

where λ is latent heat of vaporization, equal to 2,450 joules per gram at 25°C;

E is quantity of water vaporized (water-vapor flux density), in grams per square meter per second;

w' is instantaneous deviation about mean of vertical wind velocity, in meters per second;

ρ_v' is instantaneous deviation about mean of vapor density of air, in grams per cubic meter;

H is sensible-heat flux, in watts per square meter;

T_a' is instantaneous deviation about mean of temperature of air, in degrees Celsius;

ρ_a is density of air, in grams per cubic meter; and

C_p is specific heat of air, in joules per gram per degree Celsius.

The means $\overline{w'\rho_v'}$ and $\overline{w'T_a'}$ are for a given time period, commonly 10 to 20 minutes.

Measurement of the vertical transport of water vapor and heat by upward and downward motion of air parcels, called eddies, requires instruments capable of making accurate instantaneous measurements within passing eddies. Fast-response sensors and data loggers capable of statistical calculations were used to obtain field data quickly and to calculate the means from instantaneous direct measurements of vertical wind speed, vapor density, and temperature.

To measure vertical windspeed, the eddy-correlation method uses a sonic anemometer, which relies on the Doppler effect (phase shift of emitted sound waves). The sonic anemometer has two facing transducers that emit and receive sound waves. Using a 160-Hz switching rate, the transducers alternately emit and receive a 40-kHz signal. The sonic anemometer also measures the relative air-temperature change by using a fine-wire thermocouple (0.013 mm in diameter). A krypton hygrometer measures water-vapor density by detecting changes in the absorption and transmission of ultraviolet radiation by water vapor. The anemometer and hygrometer are placed within 0.07 m of each other so that both sensors measure the same eddies. By minimizing sensor separation, frequency-response corrections (Moore, 1986) are unnecessary. However, the water-vapor flux values are corrected for oxygen effects when using the krypton hygrometer (Tanner and Greene, 1989) and for density effects caused by heat and water-vapor transfer (Webb and others, 1980).

In the eddy-correlation method, the optimum frequencies for sampling eddies and calculating covariances are a function of mean wind speed and measurement height (Kaimal and others, 1972; McBean, 1972):

$$10^{-3} \leq fz/\bar{U} \leq 10\,, \qquad (5)$$

where f is frequency, in hertz;

z is measurement height above canopy, in meters; and

$\bar{U}$ is mean wind speed, in meters per second.

The measurement height is the distance above the effective canopy, which is a function of both the average canopy height and the density of ground cover. The upper limit of $fz/\bar{U}$ is dictated by the response of the sensors, and the lower limit by the averaging time needed by the data logger for longer period eddies. When working within a few meters of the ground surface, measurements typically are made at about 10 Hz and covariances are calculated every 10 to 20 minutes (Tanner, 1988). In this study, the point of measurement for the eddy-correlation equipment was set at approximately 0.75 m above the canopy. The sampling interval was 10 Hz or 0.1 second, and covariances were calculated every 10 minutes and averaged over 20 minutes to obtain 20-minute ET rates.

The uncertainty involved in obtaining ET rates by the eddy-correlation method can be inferred from the size of the residual when the four independently measured components are used to solve the energy-budget equation. Ideally, the available energy (net radiation minus soil-heat flux, $R_n - G$) used to generate the turbulent components of the sensible- and latent-heat fluxes (H and λE) is equal to the sum of those fluxes (eq. 1). The residual $(R_n - G - H - \lambda E)$ equals zero in the ideal case; however, the residual generally does not equal zero because of measurement errors. The amount of the residual imbalance relative to the available energy ($R_n - G$) is termed the "relative closure" and can be expressed as a percentage:

$$C_r = \frac{R_n - G - H - \lambda E}{R_n - G} \times 100\,, \qquad (6)$$

where C_r is relative closure, in percent;

R_n is net radiation, in watts per square meter;

G is soil-heat flux, in watts per square meter;

H is sensible-heat flux, in watts per square meter;

λ is latent heat of vaporization, equal to 2,450 joules per gram at 25°C; and

E is quantity of water vaporized (water-vapor flux density), in grams per square meter per second.

Accuracy of Evapotranspiration Estimates

Recorded ET rates may not be of any greater accuracy than ±20 percent, given the dry to extremely dry field conditions at the time of monitoring. Because the Bowen-ratio method relies on all four energy terms in equation 1 to derive the ratio, the uncertainty in the ET rates is a composite of the errors introduced in measuring all the energy terms. The eddy-correlation method, however, measures each of the energy-budget terms independently, and therefore the residual of the energy-budget equation can be evaluated. Such evaluations can be used to assess the relative uncertainty in the ET rates obtained under the existing field conditions.

In the summer of 1992 additional equipment needed to estimate the available energy ($R_n - G$) was installed at the eddy-correlation field sites (4 and 5) to determine the relative uncertainty of the ET rates obtained by the eddy-correlation method. Data from these two sites then were evaluated for relative closure of the energy budget (eq. 6). At site 4, the 20-minute closures during the day (excluding the nocturnal inversion) ranged from 1 to 46 percent, and daily means of these closures ranged from 5 to 18 percent. At site 5, these daytime 20-minute closures ranged from 5 to 38 percent, and the daily means averaged 18 percent.

EVAPOTRANSPIRATION DATA

The daily ET rates obtained during the study are plotted in figure 2 and are listed in tables 2 through 7. At site 1 the greasewood community had a mean daily ET rate of 1.4 mm/d (range: 0.8 to 2.0 mm/d) in 1991 (table 2) and 0.6 mm/d (range: 0.2 to 0.9 mm/d) in 1992 (table 3). Bowen-ratio instrumentation was used at this site during both summers. The greasewood plants did not look vigorous and showed signs of stress during the 1991 summer growing season, and a larger number of the stems were dead on each bush during the 1992 summer growing season. The greasewood leaves dropped from the surviving branches prematurely throughout the summer in 1992. In 1991 during Julian days 206 through 218, the Bowen-ratio instrumentation had a voltage reference offset from 0. The daily values shown in table 2 for those Julian days were corrected to remove that offset.

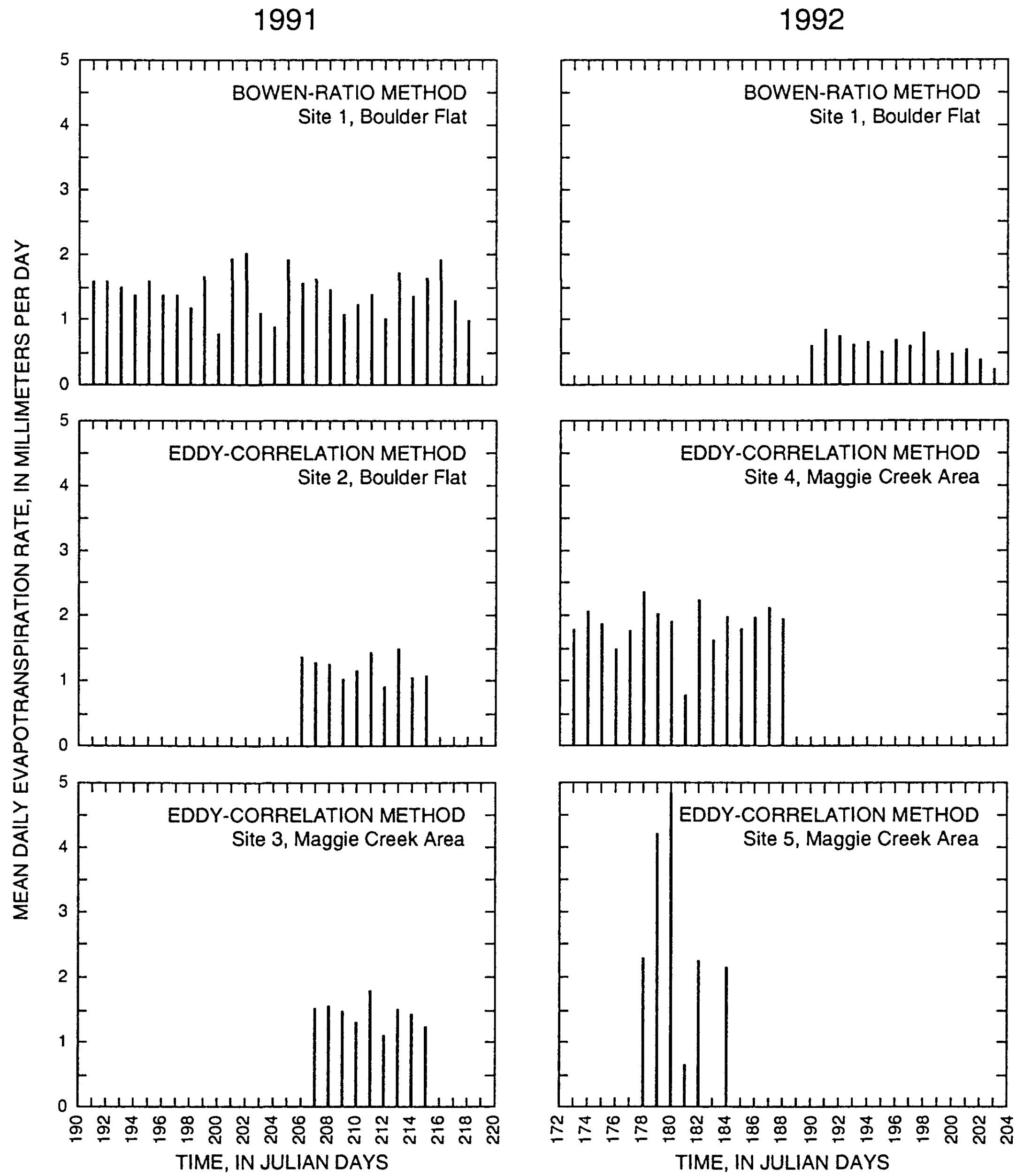

Figure 2. Daily mean evapotranspiration rates measured at five monitoring sites in Boulder Flat and in Maggie Creek Area (fig. 1) during summers of 1991 and 1992. Bars shown only for measurement periods. No data for Julian day 183 at site 5.

At site 2 the mixed sagebrush-and-greasewood community had a mean daily ET rate of 1.2 mm/d (range: 0.9 to 1.5 mm/d) in 1991 (table 4); no measurements were made at this site in 1992. Eddy-correlation instrumentation was used at site 2. For comparison, at site 1 the average ET rate was 1.4 mm/d (range: 1.0 to 1.7 mm/d) for the same 10 days of record. Given the difference in monitoring methods and monitoring uncertainty, the difference between mean ET rates (for the same time period) at these two sites in Boulder Flat may not be significant. A longer period of record at both sites would be required to define a significant difference (if any) in the ET rates.

At sites 3 (in 1991) and 4 (in 1992) the predominantly rabbitbrush community within the Maggie Creek alluvial channel deposits had mean daily ET rates of 1.4 and 1.9 mm/d, respectively (typical range:

Table 2. Evapotranspiration at site 1, Boulder Flat, July 10 through August 6, 1991, by Bowen-ratio method

Julian day	Calendar date	Evapotranspiration (millimeters per day)
191	7/10/91	1.6
192	7/11/91	1.6
193	7/12/91	1.5
194	7/13/91	1.4
195	7/14/91	1.6
196	7/15/91	1.4
197	7/16/91	1.4
198	7/17/91	1.2
199	7/18/91	1.7
200	7/19/91	.8
201	7/20/91	1.9
202	7/21/91	2.0
203	7/22/91	1.1
204	7/23/91	.9
205	7/24/91	1.9
206	7/25/91	[1]1.6
207	7/26/91	[1]1.6
208	7/27/91	[1]1.4
209	7/28/91	[1]1.1
210	7/29/91	[1]1.2
211	7/30/91	[1]1.4
212	7/31/91	[1]1.0
213	8/1/91	[1]1.7
214	8/2/91	[1]1.4
215	8/3/91	[1]1.6
216	8/4/91	[1]1.9
217	8/5/91	[1]1.3
218	8/6/91	[1]1.0
Average		1.4

[1] Values corrected for voltage offset.

Table 3. Evapotranspiration at site 1, Boulder Flat, July 8 through 21, 1992, by Bowen-ratio method

Julian day	Calendar date	Evapotranspiration (millimeters per day)
190	7/8/92	0.6
191	7/9/92	.9
192	7/10/92	.8
193	7/11/92	.6
194	7/12/92	.7
195	7/13/92	.5
196	7/14/92	.7
197	7/15/92	.6
198	7/16/92	.8
199	7/17/92	.5
200	7/18/92	.5
201	7/19/92	.6
202	7/20/92	.4
203	7/21/92	.2
Average		.6

Table 4. Evapotranspiration at site 2, Boulder Flat, July 25 through August 3, 1991, by eddy-correlation method

Julian day	Calendar date	Evapotranspiration (millimeters per day)
206	7/25/91	1.4
207	7/26/91	1.3
208	7/27/91	1.3
209	7/28/91	1.0
210	7/29/91	1.2
211	7/30/91	1.4
212	7/31/91	.9
213	8/1/91	1.5
214	8/2/91	1.0
215	8/3/91	1.1
Average		1.2

1 to 2 mm/d) (tables 5 and 6). Eddy-correlation instrumentation was used at both sites. Because plants showed no signs of stress from the continuing drought conditions, plant roots apparently were receiving sufficient moisture from the alluvial channel deposits. At site 4 during Julian days 178 through 188 of 1992, the krypton hygrometer (used to measure the vapor density needed in eq. 3) became inoperative, and ET rates were obtained by solving equation 1 for the latent-heat flux using the other measured values.

At site 5 the meadow grass had mean daily ET rates of 2.7 mm/d (typical range: 2 to 4 mm/d) in 1992 (table 7). Eddy-correlation instrumentation was used at this site. The moist soils at site 5 yielded the highest ET rates estimated during this study. The soils contained a high volume of fibric material that resulted in a low bulk density and a high volumetric water content (39 percent by volume).

Table 5. Evapotranspiration at site 3, Maggie Creek Area, July 26 through August 3, 1991, by eddy-correlation method

Julian day	Calendar date	Evapotranspiration (millimeters per day)
207	7/26/91	1.5
208	7/27/91	1.6
209	7/28/91	1.5
210	7/29/91	1.3
211	7/30/91	1.8
212	7/31/91	1.1
213	8/1/91	1.5
214	8/2/91	1.4
215	8/3/91	1.2
Average		1.4

Table 6. Evapotranspiration at site 4, Maggie Creek Area, June 21 through July 6, 1992, by eddy-correlation method

Julian day	Calendar date	Evapotranspiration (millimeters per day)
173	6/21/92	1.8
174	6/22/92	2.1
175	6/23/92	1.9
176	6/24/92	1.5
177	6/25/92	1.8
178	6/26/92	[1]2.4
179	6/27/92	[1]2.0
180	6/28/92	[1]1.9
181	6/29/92	[1].8
182	6/30/92	[1]2.2
183	7/1/92	[1]1.6
184	7/2/92	[1]2.0
185	7/3/92	[1]1.8
186	7/4/92	[1]2.0
187	7/5/92	[1]2.1
188	7/6/92	[1]2.0
Average		1.9

[1] Evapotranspiration rates calculated from residual values.

Table 7. Evapotranspiration at site 5, Maggie Creek Area, June 26 through July 2, 1992, by eddy-correlation method

[no data for Julian day 183]

Julian day	Calendar date	Evapotranspiration (millimeters per day)
178	6/26/92	2.3
179	6/27/92	4.2
180	6/28/92	4.8
181	6/29/92	.7
182	6/30/92	2.3
184	7/2/92	2.1
Average		2.7

SUMMARY AND CONCLUSIONS

The results from this study demonstrate that ET rates can be obtained even under dry to extremely dry conditions in Boulder Flat and in the Maggie Creek Area. During the summers of 1991 and 1992, two methods of estimating ET were tested, the Bowen-ratio method and the eddy-correlation method. Daily ET rates ranged from 0.2 to 2.0 mm/d at the two sites in Boulder Flat and ranged from 0.7 to 4.8 mm/d at the three sites in the Maggie Creek Area. Measurements were made during the fifth and sixth years of a continuing drought.

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