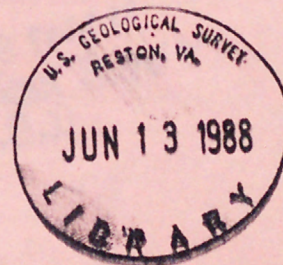
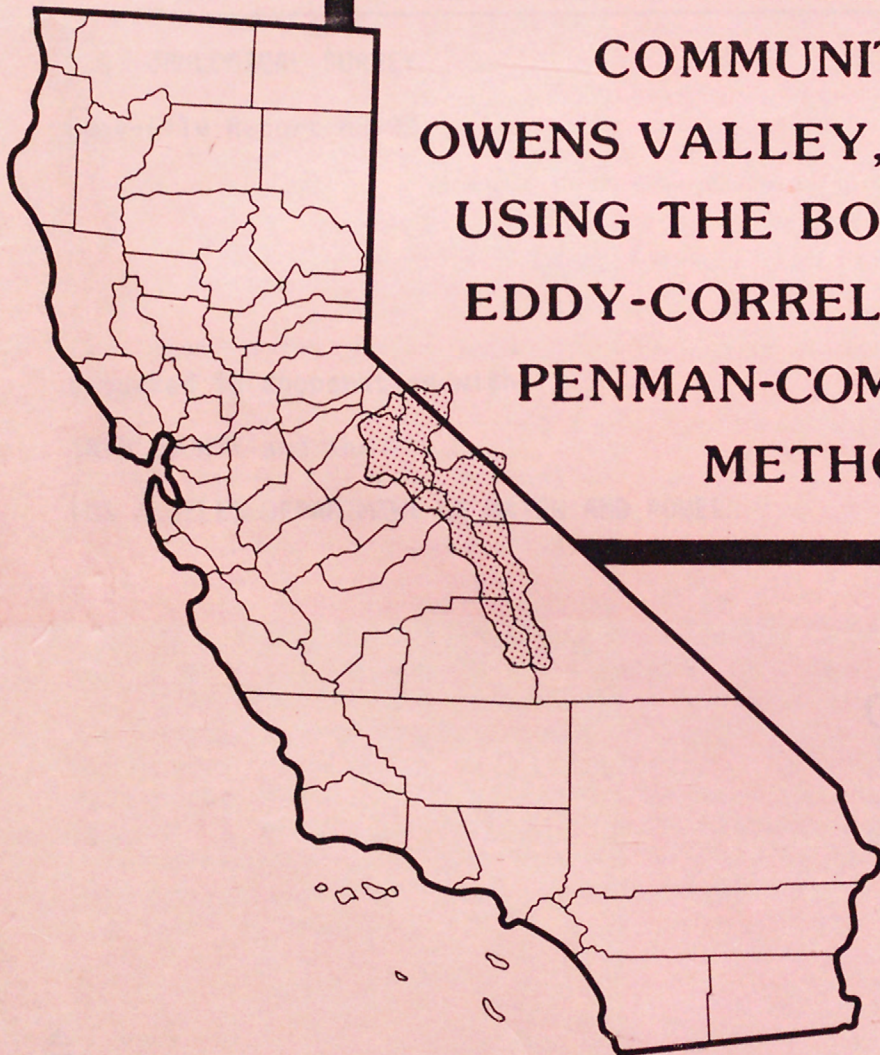


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USING THE BOWEN-RATIO,  
EDDY-CORRELATION, AND  
PENMAN-COMBINATION  
METHODS**



**U. S. GEOLOGICAL SURVEY**  
**Open-File Report 88-92**

*Tw anal*

**Prepared in cooperation with  
INYO COUNTY and the LOS ANGELES DEPARTMENT  
OF WATER AND POWER**





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By Lowell F. W. Duell, Jr.

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INYO COUNTY and the  
LOS ANGELES DEPARTMENT OF WATER AND POWER

Open-file report  
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## SYMBOLS USED IN TEXT

A	Empirical coefficient
a	Regression constant
B	Empirical coefficient
b	Regression constant
$C_p$	Heat capacity of air
d	Zero plane displacement
$\frac{d}{dV}$	Voltage gradient
$\frac{dT}{dx}$	Temperature gradient in direction x
$\frac{d\rho_v}{dV}$	Vapor-density voltage gradient
$\frac{d\rho_v}{dz}$	Vapor-density gradient in direction of flux
E	Quantity of water evaporated
ET	Evapotranspiration
G	Soil-heat flux
H	Sensible-heat flux
h	Average crop height
K	Attenuation coefficient
$K_h$	Eddy-diffusion coefficient for heat transport
$K_v$	Eddy-diffusion coefficient for vapor transport
k	Von Karman's constant equal to 0.4
N	Number of samples
P	Vapor pressure

$R$	Water-vapor specific gas constant
$R_n$	Net radiation
$r^2$	Coefficient of determination
$r_H$	Heat-diffusion resistance
$r_v$	Vapor-diffusion resistance
$S$	Slope of the saturated vapor density
$s$	Standard error of the estimate
$T$	Air temperature
$T_w$	Wet-bulb temperature
$u$	Mean windspeed
$V$	Hygrometer voltage output
$V_o$	Unattenuated voltage output
$w$	Vertical wind velocity
$x$	Path length
$\bar{X}$	Algebraic mean
$Z$	Instrument height
$Z_h$	Roughness parameter for heat transfer
$Z_m$	Roughness parameter for momentum
$\beta$	Bowen ratio
$\gamma$	Psychrometer constant
$\gamma^*$	Apparent psychrometer constant
$\Delta T$	Difference in air temperature at two heights
$\Delta \rho_v$	Difference in vapor density at two heights
$\lambda$	Latent-heat of vaporization
$\lambda E$	Latent-heat flux
$\lambda E_p$	Potential latent-heat flux
$\rho$	Air density
$\rho_a$	Corrected air density
$\rho_v$	Vapor density
$\rho'_v$	Saturated vapor density
$\rho_{vd}$	Vapor-density deficit
$\sigma$	Standard deviation
$\log$	Base 10 logarithm
$\ln$	Base e logarithm
EXP	Exponential ( $\exp x = e^x$ , where $e = 2.7183 \dots$ )
'	Instantaneous deviation from the mean
—	Means for a 30-minute period

## CONVERSION FACTORS

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Metric (International System) units are used in this report. For those readers who prefer to use inch-pound units, conversion factors for the terms used in this report are listed below:

<u>Multiply metric unit</u>	<u>by</u>	<u>To obtain inch-pound unit</u>
<u>Area</u>		
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
<u>Density</u>		
grams per cubic meter (g/m <sup>3</sup> )	0.4370	grains per cubic foot (gr/ft <sup>3</sup> )
	$6.2428 \times 10^{-5}$	pounds per cubic foot (lb/ft <sup>3</sup> )
<u>Energy</u>		
joule (J)	$9.4787 \times 10^{-4}$	British thermal unit (BTU)
	0.2388	calorie (cal)
<u>Energy and Area Time</u>		
watts per square meter (W/m <sup>2</sup> )	$5.2895 \times 10^{-3}$	British thermal unit per square foot per minute [(BTU/ft <sup>2</sup> )/min]
calories per square centimeter per minute [(cal/cm <sup>2</sup> )/min]	$1.434 \times 10^{-3}$	British thermal unit per square foot per minute [(BTU/ft <sup>2</sup> )/min]
<u>Energy and Mass</u>		
joules per gram (J/g)	0.4303	British thermal unit per pound (BTU/lb)
<u>Length</u>		
nanometer (nm)	$0.3937 \times 10^{-3}$	mil
micrometer (μm)	0.3937	mil
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)

<u>Multiply metric unit</u>	<u>by</u>	<u>To obtain inch-pound unit</u>
<u>Mass</u> gram (g)	$2.205 \times 10^{-3}$	pounds (lb)
<u>Mass flux</u> grams per square meter (g/m <sup>2</sup> )	17.71	pounds per square foot per day [(lb/ft <sup>2</sup> )/d]
<u>Power</u> watt (W)	3.412 $1.340 \times 10^{-3}$ 0.2388	British thermal unit per hour (BTU/h) horsepower calories per second (cal/s)
<u>Pressure</u> kilopascal (kPa)	0.2953 0.1450 10	inches of mercury (in. Hg) pound per square inch (lb/in <sup>2</sup> ) millibar (mb)
<u>Temperature</u> degrees Celsius (°C) Kelvin (°K)	1.8 °C + 32 (°K - 273.15)1.8 + 32	degree Fahrenheit (°F) °F
<u>Velocity or Rate</u> meter per second (m/s)	2.237	mile per hour (mi/h)
<u>Volume</u> cubic meter (m <sup>3</sup> )	$8.107 \times 10^{-4}$	acre-foot (acre-ft)

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



ESTIMATES OF EVAPOTRANSPIRATION IN ALKALINE SCRUB AND MEADOW COMMUNITIES  
OF OWENS VALLEY, CALIFORNIA, USING THE BOWEN-RATIO,  
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ABSTRACT

In Owens Valley, evapotranspiration (ET) is one of the largest components of outflow in the hydrologic budget and the least understood. ET estimates for December 1983 through October 1985 were made for seven representative locations selected on the basis of geohydrology and the characteristics of phreatophytic alkaline scrub and meadow communities. The Bowen-ratio, eddy-correlation, and Penman-combination methods were used to estimate ET. The results of the analyses appear satisfactory when compared to other estimates of ET. Results by the eddy-correlation method are for a direct and a residual latent-heat flux that is based on sensible-heat flux and energy budget measurements. Penman-combination potential ET estimates were determined to be unusable because they overestimated actual ET. Modification in the psychrometer constant of this method to account for differences between heat-diffusion resistance and vapor-diffusion resistance permitted actual ET to be estimated.

The methods described in this report may be used for studies in similar semiarid and arid rangeland areas in the Western United States. Meteorological data for three field sites are included in the appendix of this report. Simple linear regression analysis indicates that ET estimates are correlated to air temperature, vapor-density deficit, and net radiation. Estimates of annual ET range from 300 millimeters at a low-density scrub site to 1,100 millimeters at a high-density meadow site. The monthly percentage of annual ET was determined to be similar for all sites studied.

## INTRODUCTION

Owens Valley is a source of water for the city of Los Angeles. Much of the valley's surface-water inflow is diverted and exported to the Los Angeles area through an aqueduct system. During periods of low surface-water runoff, water requirements are augmented by ground water pumped from the valley's aquifer system. About one-half of the annual natural recharge to the valley is removed from the system by evapotranspiration (ET). ET includes transpiration by phreatophytic alkaline plant (scrub and meadow) communities and evaporation from open-water and soil surfaces.

This study was accomplished as part of a much larger effort. In 1982 the U.S. Geological Survey, in cooperation with Inyo County and the Los Angeles Department of Water and Power, began a series of comprehensive studies to define the ground-water system in Owens Valley and to determine the effects that ground-water withdrawals might have on native vegetation. These studies are discussed more fully by Hollett (1987). The results of the studies, as well as a comprehensive summary, are presented in a U.S. Geological Survey Water-Supply Paper series as the interpretive products of the studies become available. The series consists of eight chapters as follows:

- A. A summary of the hydrologic system and soil-water-plant relations in Owens Valley, California, 1982-87, with an evaluation of management alternatives,
- B. Hydrogeology and water resources of Owens Valley, California,
- C. Estimating soil matric potential in Owens Valley, California,
- D. Osmotic potential and projected drought tolerances of four phreatophytic shrub species in Owens Valley, California, with a section on plant-water relations,
- E. Estimates of evapotranspiration in alkaline scrub and meadow communities of Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods (this report),
- F. Influence of changes in soil water and depth to ground water on transpiration and canopy of alkaline scrub communities in Owens Valley, California,
- G. Vegetation and soil water responses to changes in precipitation and depth to ground water in Owens Valley, California, and
- H. Numerical simulation and system analysis of the ground-water-flow system in Owens Valley, California.

## Purpose and Scope

Evapotranspiration (ET) is one of the largest components of outflow in the hydrologic budget of Owens Valley; it is the least understood. The purpose of this report is to provide estimates of ET that can be used to verify and calibrate models developed as part of other phases of the overall study. This report describes the instrumentation and techniques used to estimate ET in Owens Valley. This report also compares monthly and annual estimates of ET with results of similar studies to improve the methods for measuring ET directly from rangeland vegetation.

The scope of the study included descriptions of meteorological measurements and comparisons of estimates of ET from December 1983 through October 1985. ET was estimated by use of three micrometeorological methods--the Bowen-ratio method used during the growing season, the eddy-correlation method also used during the growing season, and the Penman-combination method used continuously throughout the study period. Seven sites were selected in the study area to make estimates of ET (fig. 1). At sites C, F, and L meteorological data were recorded continuously; at sites A, E, G, and J the data were recorded intermittently. The letters are local identifiers for the sites in the Owens Valley cooperative studies and align in a north to south progression. The Bowen-ratio and Penman-combination methods were used at the continuous-record sites. The eddy-correlation method was used at the intermittent-record sites.

## Acknowledgments

Lysimeter data were provided by Robert J. Reginato, U.S. Department of Agriculture Water Conservation Laboratory, Phoenix, Arizona. The California Irrigation Management Information System project was partly funded by the Los Angeles Department of Water and Power. Data from that project were provided in cooperation with Richard L. Synder and David A. Goldhammer, University of California at Davis, and P. Dean Smith, University of California Cooperative Extension, Inyo County. The following persons assisted in providing information on vegetation, soils, and sites: (1) David P. Groeneveld, Daniel C. Warren, and Daniel S. Munk, Inyo County; (2) Russell H. Rawson, Patti J. Novak, and Paula J. Hubbard, Los Angeles Department of Water and Power; (3) Leonard W. Jolley and Fred A. Fischer, U.S. Soil Conservation Service. U.S. Geological Survey personnel who assisted at various times and different levels include Edwin P. Weeks who provided invaluable assistance and guidance on the collection and interpretation of meteorological data for ET calculations; Alex M. Sturrock (technical advice); Michael R. Simpson (instrumentation design and installation); Peter J. Armstrong (field assistance); and finally, Diane M. Nork who assisted in data collection and reduction; her persistence and perseverance are gratefully acknowledged.

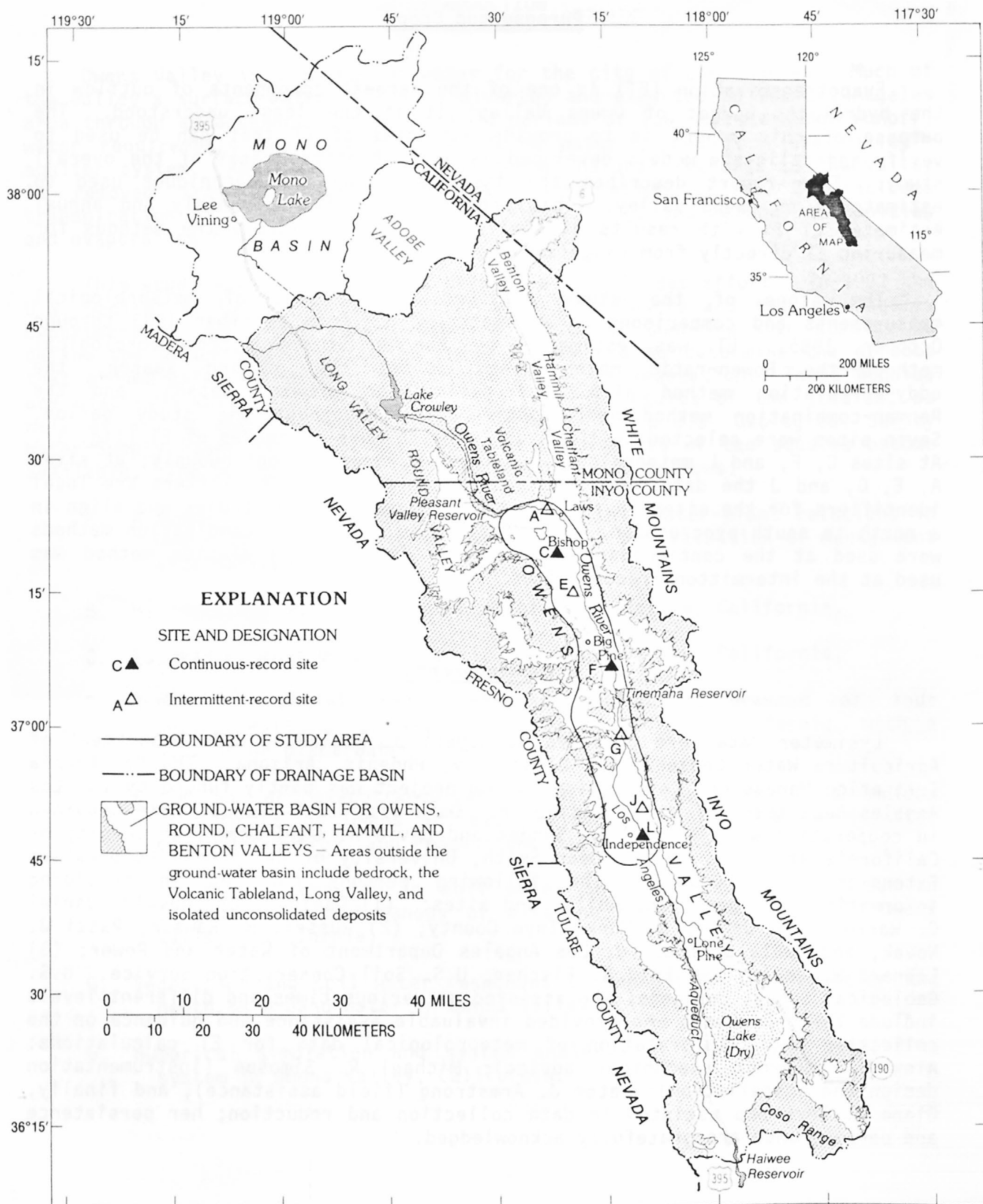


Figure 1. Location of the study area and study sites.

## DESCRIPTION OF STUDY AREA

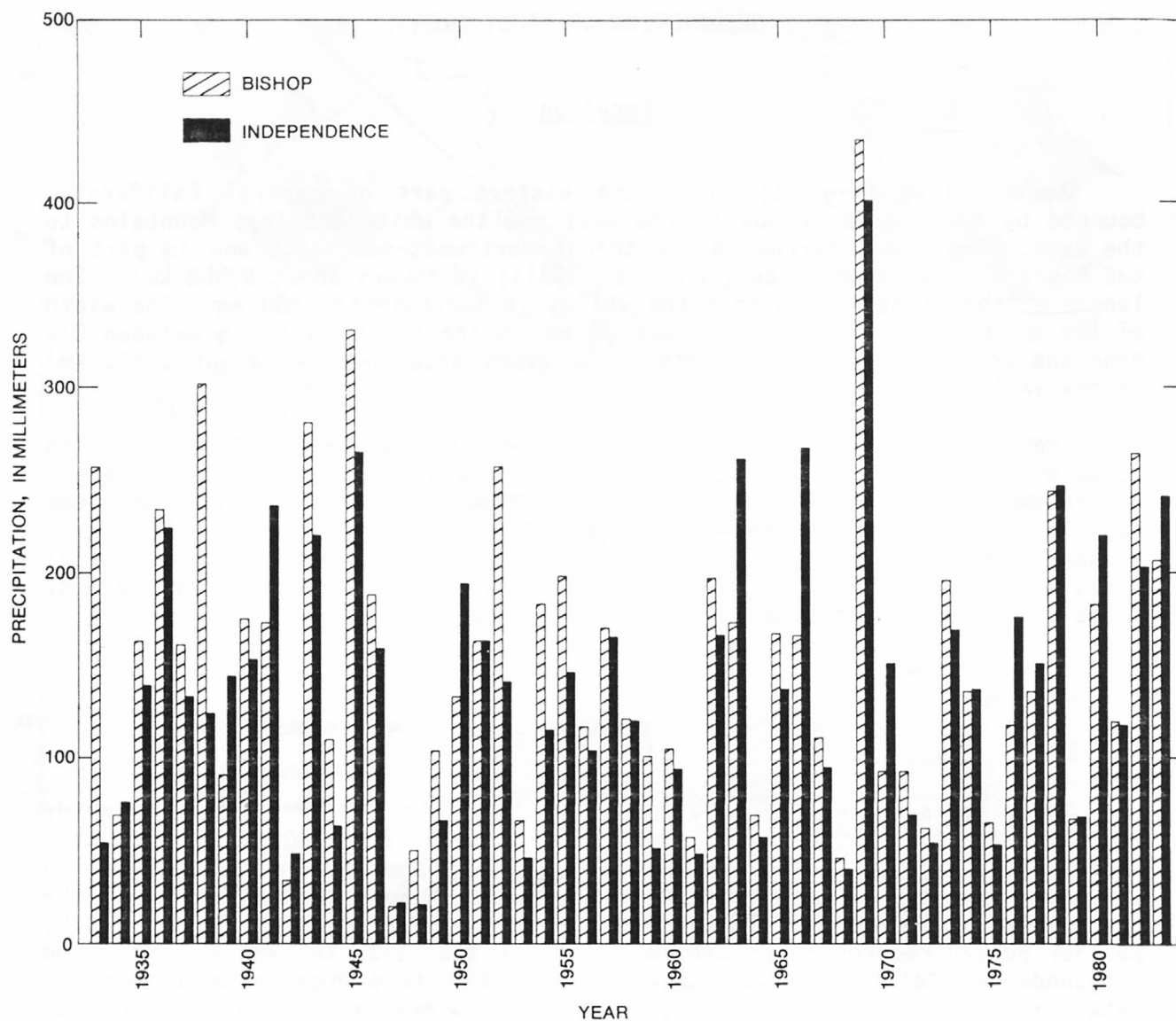
### Location

Owens Valley (fig. 1) is in the eastern part of central California, bounded by the Sierra Nevada to the west and the White and Inyo Mountains to the east. The long, narrow valley trends northwest-southeast and is part of the Basin and Range province (Fenneman, 1931); it covers about 8,500 km<sup>2</sup>. The length of the study area within the valley is approximately 80 km. The width of the study area ranges from about 32 km in the north to 16 km between Big Pine and Independence in the south. The study area includes about 1,300 km<sup>2</sup> of the valley floor.

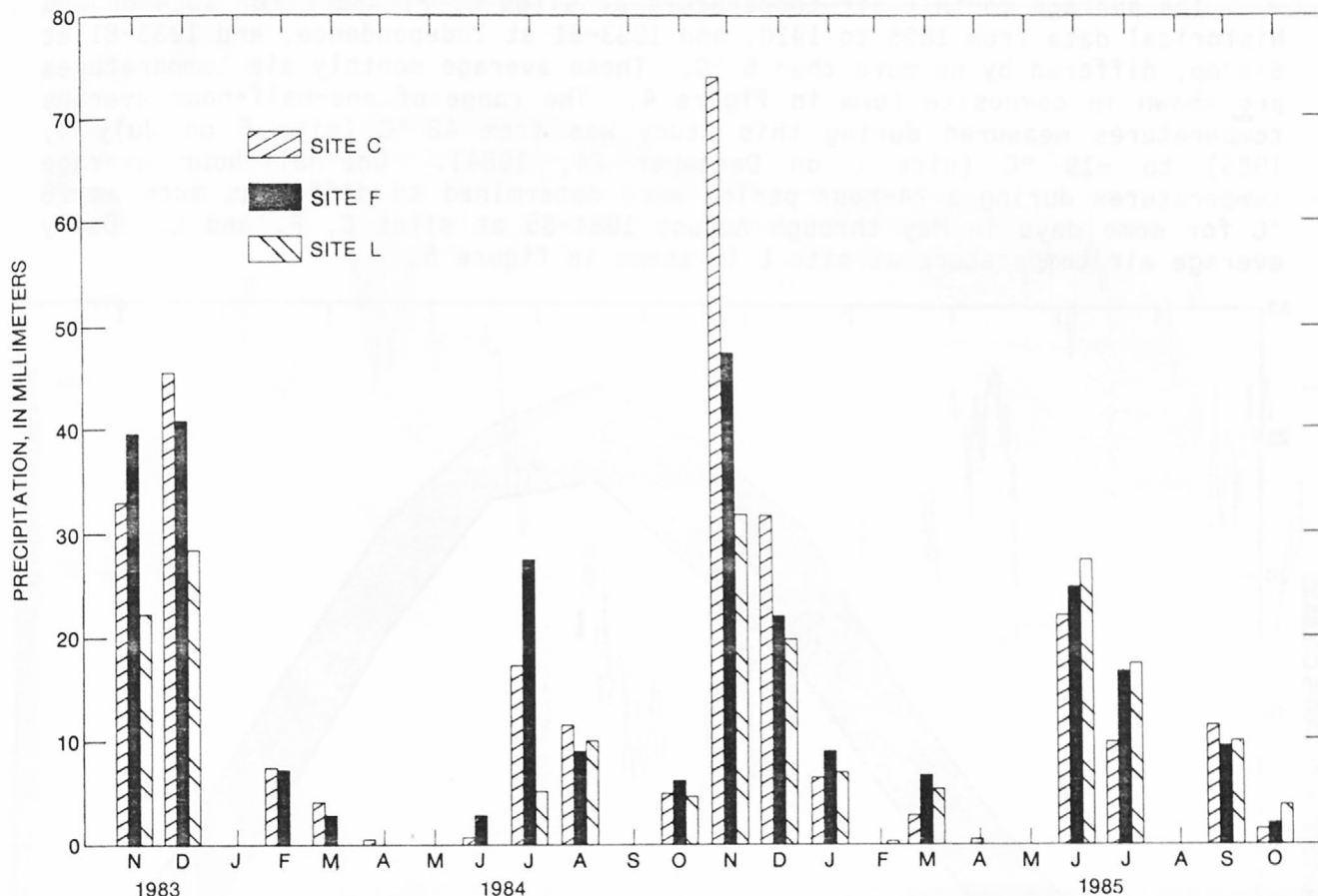
The valley floor between Laws and Independence ranges from 1,160 to 1,260 m above sea level and has a slope that averages 1.4 m/km. The adjacent Sierra Nevada to the west rise to an altitude of more than 4,300 m. Lee (1912) calculated the gradient of slopes on the eastern face of the Sierra Nevada to be an average of 285 to 380 m/km and the slopes of the alluvial deposits flanking the range to be from 65 to 115 m/km. The slopes of the west faces of the White and Inyo Mountains range from 130 to 380 m/km.

### Climate

The climate in the Owens Valley study area (fig. 1) is semiarid to arid; mean annual precipitation on the valley floor ranges from 100 to 150 mm. Mean annual precipitation for the region ranges from 100 mm on the valley floor to 1,000 mm near the crest of the Sierra Nevada. More than two-thirds of the precipitation occurs during the months of November through March. U.S. Weather Bureau records of annual precipitation from 1933 to 1983 at Bishop and Independence, California, are shown in figure 2 (Los Angeles Department of Water and Power, written commun., 1984). The annual precipitation for 1984 was 150 mm at site C, 160 mm at site F, and 80 mm at site L. Monthly precipitation totals recorded during this study from December 1983 to October 1985 at sites C, F, and L are shown in figure 3. The largest single one-day rain event during this study was 33 mm on June 2, 1985, at site L. Precipitation is greatest on the west side of Owens Valley as a result of the high altitude of the Sierra Nevada and the prevailing direction of airmass movement. Moisture-laden airmasses from the west lose much of their moisture in passing over the Sierra Nevada, and as a consequence, rainfall is very light in the central part of the valley.



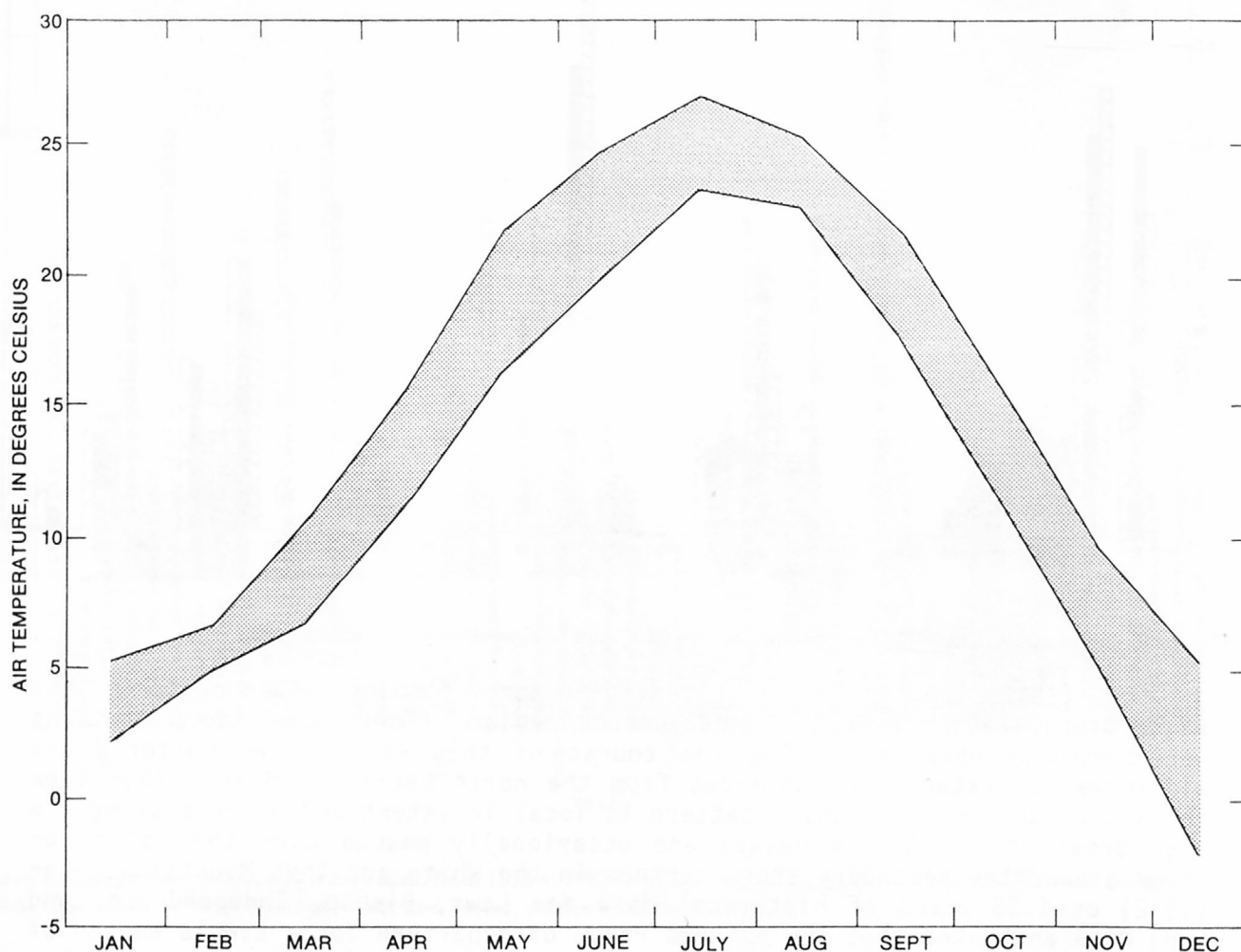
**Figure 2.** Comparison of annual precipitation from 1933 to 1983 at Bishop and Independence National Weather Bureau stations (Los Angeles Department of Water and Power, written commun., 1984).



**Figure 3.** Comparison of monthly precipitation at sites C, F, and L, November 1983-October 1985.

Lee (1912), during 1908-11, identified three distinct storm patterns that yield precipitation over the Independence region. These same storm patterns were commonly observed during the course of this study. Two patterns are widespread in extent, one advances from the north Pacific and the other from the south Pacific. The third pattern is local in extent and gathers along the high crest of the Sierra Nevada and occasionally passes over the valley or forms around the secondary storm centers in the White and Inyo Mountains. Lee (1912) used 26 years of historical data for Laws, Bishop, Independence, and Lone Pine and noted that the extreme range of departure for a single season of mean annual precipitation on the valley floor was from 20 percent to more than 350 percent of normal. A similar range of measured precipitation is shown for the 1933-83 annual rainfall at Bishop and Independence (fig. 2).

The average monthly air temperature at sites C, F, and L for 1984-85 and historical data from 1895 to 1910, and 1933-81 at Independence, and 1933-81 at Bishop, differed by no more than 6 °C. These average monthly air temperatures are shown in composite form in figure 4. The range of one-half-hour average temperatures measured during this study was from 42 °C (site F on July 4, 1985) to -19 °C (site L on December 24, 1984). One-half-hour average temperatures during a 24-hour period were determined to differ as much as 26 °C for some days in May through August 1984-85 at sites C, F, and L. Daily average air temperature at site L is shown in figure 5.



**Figure 4.** Range of the average monthly air temperature for study sites C, F, and L, 1984-85; and Bishop and Independence National Weather Bureau stations, 1895-1981 (Lee, 1912; Los Angeles Department of Water and Power, written commun., 1984; and this study).

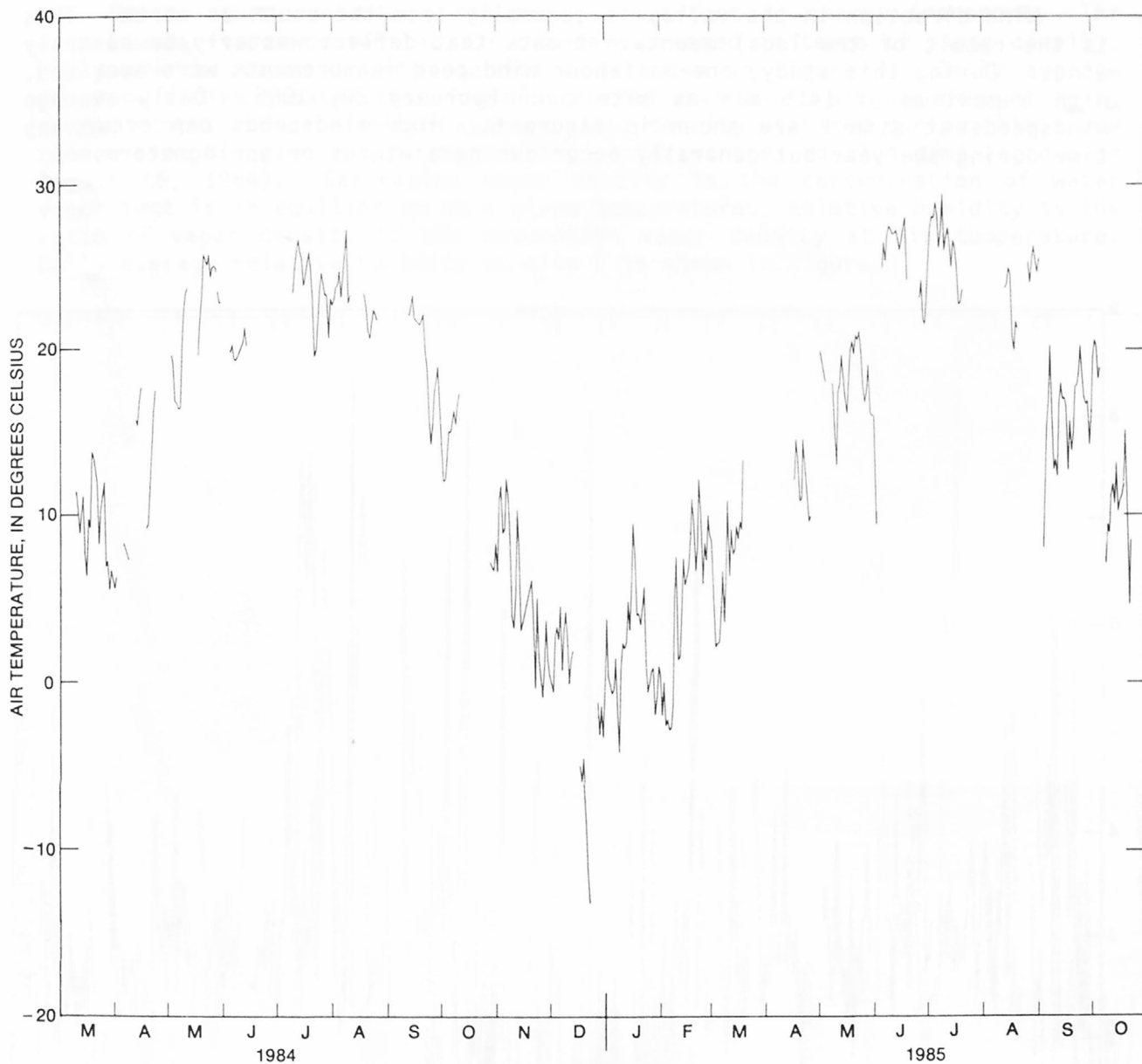


Figure 5. Daily average air temperature at site L, March 1984-October 1985.

Wind direction in the valley is generally from the south or north. This is the result of the local mountain fronts that deflect westerly or easterly winds. During this study, one-half-hour windspeed measurements were averaged, with a maximum of 14.5 m/s at site L on February 20, 1985. Daily average windspeeds at site F are shown in figure 6. High windspeeds can occur any time during the year but generally occur during a winter or spring storm.

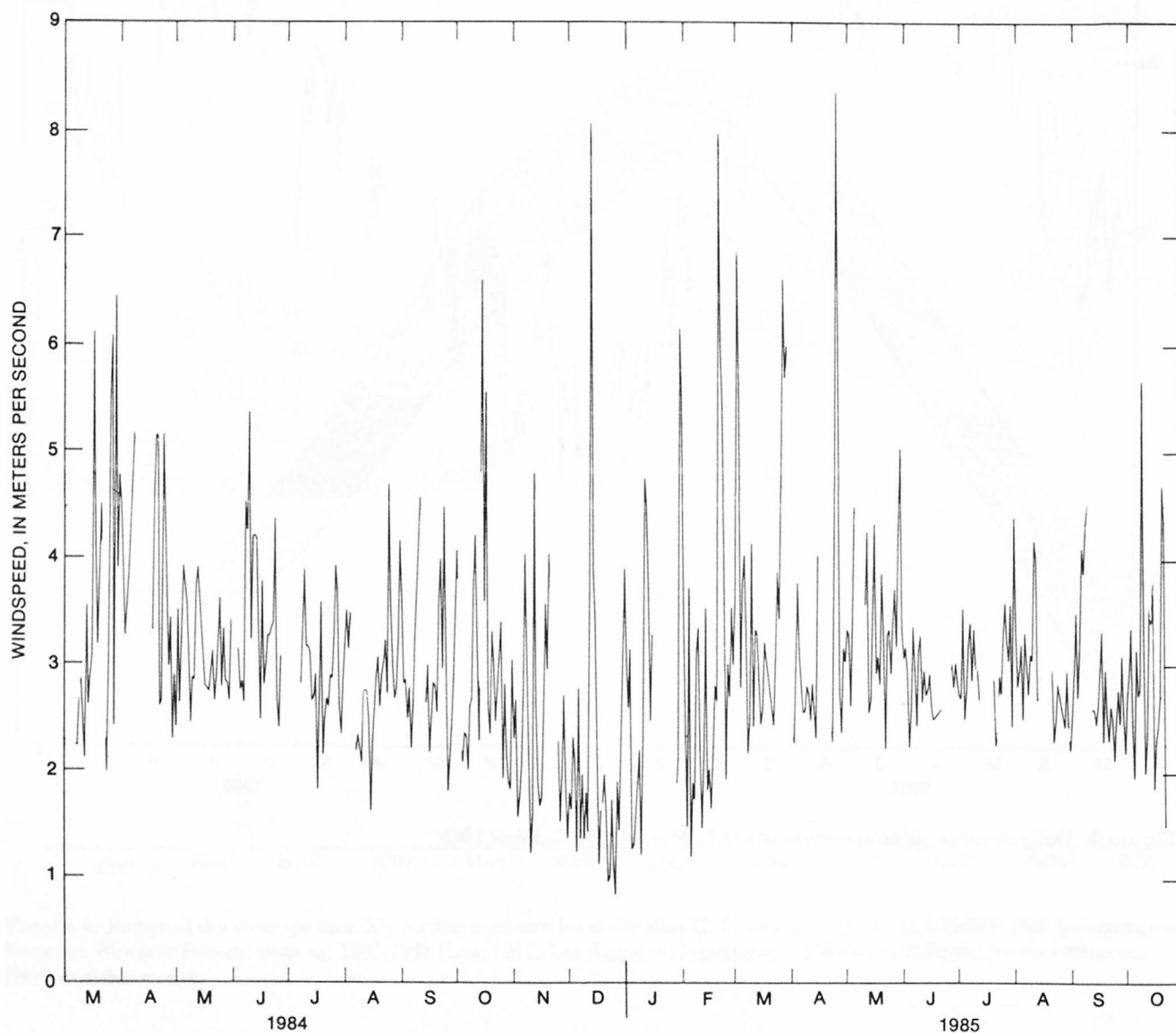


Figure 6. Daily average windspeed at site F, March 1984-October 1985.

The moisture content of the air is important in energy transport. The actual water-vapor content in air can be expressed in terms of vapor density. Daily average vapor density at site L is shown in figure 7. Daily average vapor densities greater than  $7 \text{ g/m}^3$  occurred when moist air was brought in by summer storms. One-half-hour average vapor density measured during this study ranged from  $0.5 \text{ g/m}^3$  (many times during winter months) to  $17.4 \text{ g/m}^3$  (site C on August 15, 1984). Saturation vapor density is the concentration of water vapor that is in equilibrium at a given temperature. Relative humidity is the ratio of vapor density to the saturation vapor density at air temperature. Daily average relative humidity at site L is shown in figure 8.

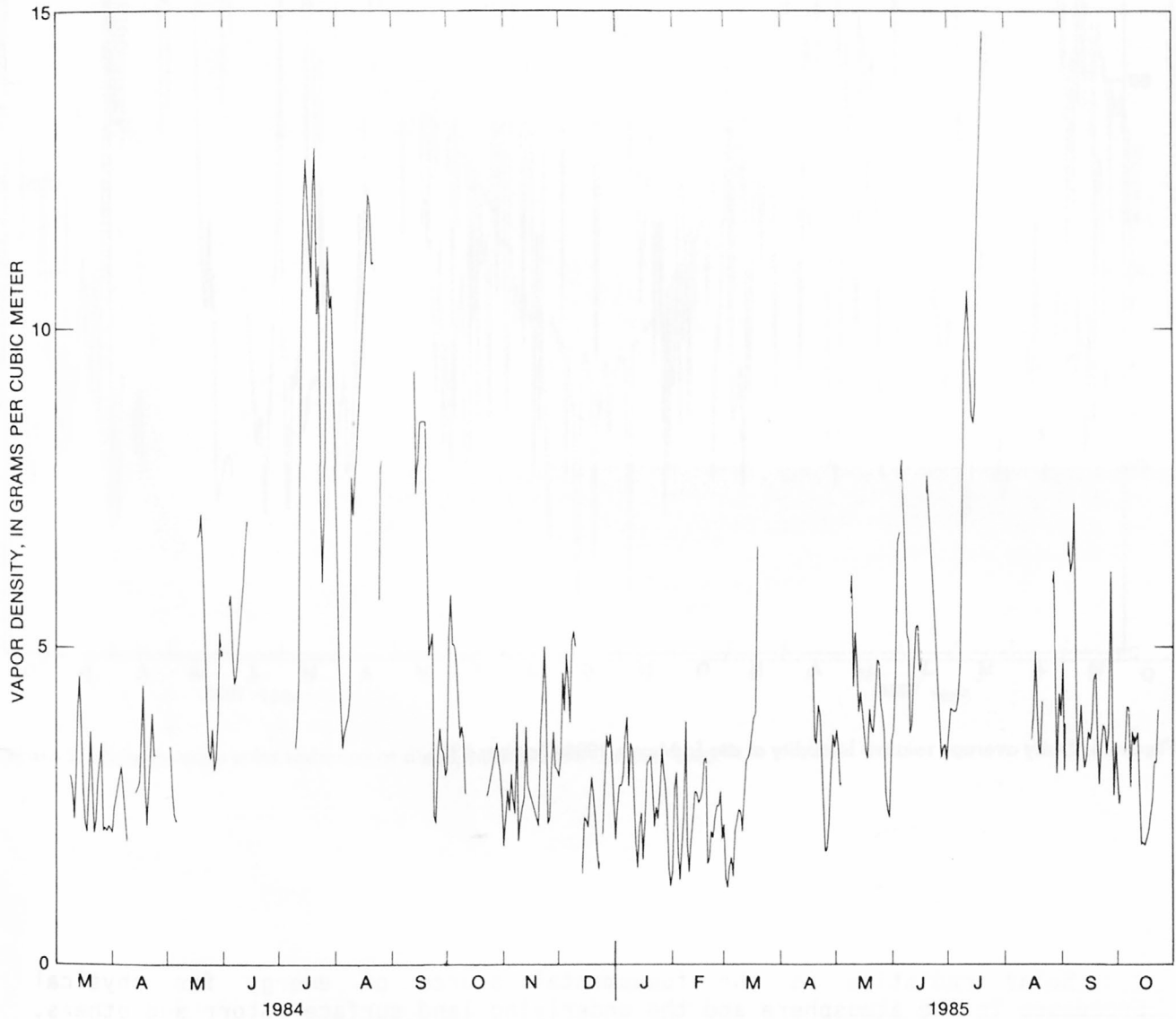
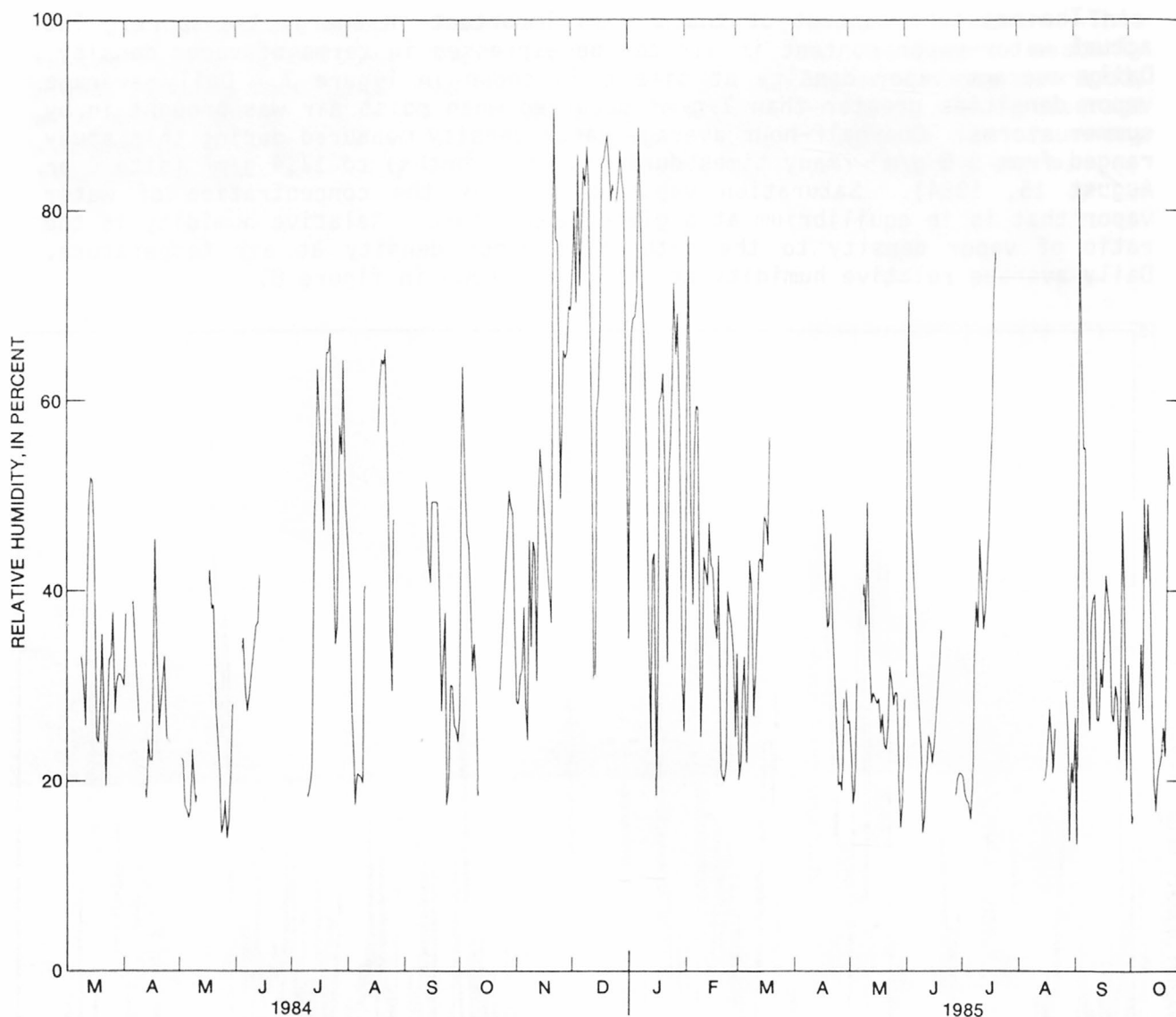
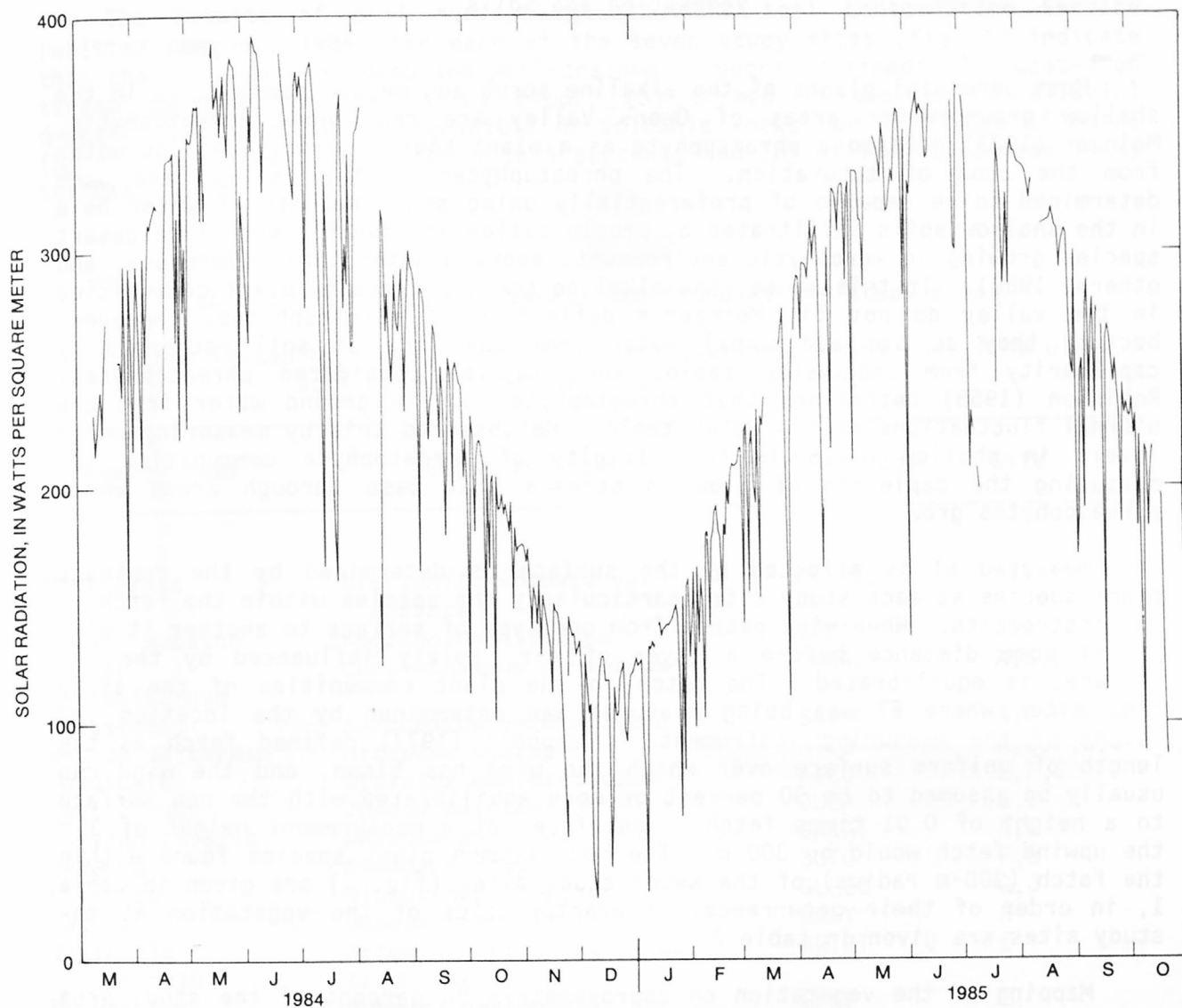


Figure 7. Daily average vapor density at site L, March 1984-October 1985.



**Figure 8.** Daily average relative humidity at site L, March 1984-October 1985.

Solar radiation is the fundamental source of energy for physical processes in the atmosphere and the underlying land surface (Storr and others, 1970). Daily average solar radiation at site C is shown in figure 9. The daily variability is a result of varying cloud cover and extent and characteristics of individual storms. Seasonal variation is caused by the rotational direction of the earth and the length of daylight hours. The 1984-85 peaks are similar. The maximum amount of solar radiation measured for a one-half-hour period during this study was  $1,185 \text{ W/m}^2$  at site C on June 12, 1984.



**Figure 9.** Daily average solar radiation at site C, March 1984-October 1985.

## Vegetation and Soils

Most perennial plants of the alkaline scrub and meadow communities in the shallow ground-water areas of Owens Valley are considered phreatophytic. Meinzer (1923) defined a phreatophyte as a plant that regularly obtains water from the zone of saturation. The phreatophytes in the valley have been determined to be capable of preferentially using small amounts of water held in the shallow soils infiltrated by precipitation and runoff, much like desert species growing in xerophytic environments above a water table (Sorenson, and others, 1988). In this sense, the alkaline scrub and meadow plant communities in the valley do not fit Meinzer's definition of phreatophytes. However, because they do use additional water from the zone of soil recharged by capillarity from the water table, they may be considered phreatophytes. Robinson (1958) determined that phreatophytes obtain ground water from the diurnal fluctuations of the water table. He observed this by measuring water levels in shallow wells in the vicinity of phreatophyte communities and measuring the depletion of flow in streams that pass through areas where phreatophytes grow.

Measured ET is affected by the surface as determined by the dominant plant species at each study site, particularly the species within the fetch of the instruments. When wind passes from one type of surface to another it will travel some distance before a layer of air, solely influenced by the new surface, is equilibrated. The fetch in the plant communities of the study area sites where ET was being measured was determined by the location and height of the measuring instruments. Campbell (1977) defined fetch as the length of uniform surface over which the wind has blown, and the wind can usually be assumed to be 90 percent or more equilibrated with the new surface to a height of 0.01 times fetch. Therefore, at a measurement height of 3 m the upwind fetch would be 300 m. The most common plant species found within the fetch (300-m radius) of the seven study sites (fig. 1) are given in table 1, in order of their occurrence. Characteristics of the vegetation at the study sites are given in table 2.

Mapping of the vegetation on approximately 50 percent of the study area indicates that a wide variation in species is present for the plant communities of Owens Valley (Los Angeles Department of Water and Power, written commun., 1987). Furthermore, the mapping data (July 1987) indicate that the study sites, when classified as to dominant plant cover type, occupy approximately 20 percent of the study area.

The results of soil surveys by the U.S. Soil Conservation Service (written commun., 1984) for each of the seven study sites (fig. 1) indicate that the soils are (1) deep and well-drained to poorly drained; (2) located on stream terraces or the valley floor; (3) formed in aeolian or alluvial deposits; (4) derived from granitic or volcanic rocks, or a mixture of both; (5) on slopes that range from 0 to 4 percent; and (6) of fine-to-coarse loamy texture.

Table 1.-- Most common vegetation found at the study sites

[Plants listed by order of most dominant species. Plant code from U.S. Soil Conservation Service (1982, p. 416)]

Common name	Genus and species	Plant code	Site
Salt grass	<i>Distichlis spicata</i> var. <i>stricta</i>	DISPS2	A11
Alkali sacaton	<i>Sporobolus airoides</i>	SPAI	A11
Rubber rabbitbrush	<i>Chrysothamnus nauseosus</i>	CHNA2	A,C,E,F,G,J
Greasewood	<i>Sarcobatus vermiculatus</i>	SAVE4	A,C,E,F,G
Nevada saltbrush	<i>Atriplex torreyi</i>	ATTO	A,C,F,G,J
Shadscale	<i>Atriplex confertifolia</i>	ATCO	E,F,G
Baltic rush	<i>Juncus balticus</i>	JUBA	G,L
Russian thistle	<i>Salsola kali</i> var. <i>tennifolia</i>	SAKAT	A,C
Inkweed	<i>Suaeda torreyana</i>	SUTO	F,G
Licorice	<i>Glycyrrhiza lepidota</i>	GLLE3	G,J
Bassia	<i>Bassia hyssopifolia</i>	BAHY	A
Basin big sagebrush	<i>Artemisia tridentata</i> var. <i>tridentata</i>	ARTRT	E
Mormon tea	<i>Ephedra nevadensis</i>	EPNE	E
Little leaf horsebrush	<i>Tetradymia galbrata</i>	TEGL	E
Iodine bush	<i>Allenrolfea occidentalis</i>	ALOC2	L
Beardless wild rye	<i>Leymus triticoides</i>	LETR	L

Table 2.--Vegetation characteristics and water-level data for 1984 at the study sites

[Data from aerial photographs, transect studies, and vegetation mapping (Los Angeles Department of Water and Power, written commun., 1984 and 1987). Average plant height determined for adult plants by species with respect to species density and percent cover. Most common plant type: Plant code given in table 1. Plants listed in order of most dominant species]

Site	Total vegetation cover (percent)	Average plant height (meters)	Most common plant type	Range of water level, in meters below land-surface datum
A	42	0.3-0.6	SPAI SAKAT BAHY <sup>1</sup> DISPS2 <sup>1</sup>	3.2-4.7
C	35	0.5	DISPS2 CHNA2 SPAI ATT0 SAVE4	3.1-3.5
E	26	0.3-0.5	CHNA2 SPAI EPNE ARTRT DISPS2 <sup>1</sup> SAVE4 <sup>1</sup>	3.1-3.3
F	24	0.3-0.5	DISPS2 SAVE4 SPAI ATT0	2.4-2.7
G	33	0.3-0.5	DISPS2 SPAI CHNA2 SAVE4	2.2-2.7
J	50	0.5-0.6	ATT0 SPAI CHNA2 DISPS2 GLLE3	1.4-2.2
L	72	0.3-0.5	DISPS2 SPAI JUBA	0.0-1.2

<sup>1</sup>Percentage of composition approximately the same; therefore equally dominant.

## Hydrologic System

Pakiser and others (1964) determined that Owens Valley is filled with a complex assortment of clay, silt, sand, gravel, and volcanic material to a depth of approximately 2,400 m. The fine silt, clay, indurated layers, and compact soil compositions are vertical and horizontal barriers to ground-water movement. Valley-fill sediments can be separated into glacial deposits, alluvial fan deposits, lakebed on valley-floor deposits, and formations derived from volcanic materials.

Hollett and others (U.S. Geological Survey, written commun., 1987) describe the geologic framework and water resources of the hydrologic system in Owens Valley. Under steady-state conditions, inflow is equal to outflow and the change in storage is zero. The Owens Valley is a closed basin that terminates at Owens Lake (fig. 1). The main source of inflow to the valley is runoff from precipitation and snowmelt in the Sierra Nevada and the White and Inyo Mountains. A lesser source is direct precipitation on the valley floor. Many small tributaries flow from the surrounding mountains directly into the Owens River, the main valley stream course (fig. 1). Owens Lake has usually been dry during recent years because the Owens River infrequently flows directly into it. Most of the outflow of ground and surface water from the valley is through ET and exported water.

Water levels were recorded continuously during 1984 at wells located within 150 m of each of the seven study sites. The range of ground-water levels at these sites is shown in table 2. Ground-water levels ranged from land surface to 4.7 m below land surface at these wells and declined no more than 1.5 m in a year.

### METHODS AND DAILY EVAPOTRANSPIRATION ESTIMATES

The net transfer of energy into and out of any given system at the Earth's surface can be expressed in terms of an energy budget. The main assumption for use of the energy-budget method is that input equals output. For this study the net radiation flux (input) was considered positive toward the crop or soil surface and the other fluxes (output) were considered positive away from the crop or soil surface. The energy-budget method relies on the fact that most of the incoming energy not lost by reflected or emitted-back radiation (net radiation) or to heat storage in the soil (soil-heat flux) is lost by air warming (sensible-heat flux) or by water evaporating (latent-heat flux). Because ET is a substantial component of the energy budget, theoretically, the ET rate may be calculated by estimating all of the other elements in the energy-budget equation. If the energy expended for photosynthesis, plant respiration, and heat storage in the crop canopy are neglected, the equation for the energy budget at the Earth's surface can be expressed as:

$$R_n - G - H - \lambda E = 0, \quad (1)$$

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

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

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

$\lambda E$  is the latent-heat flux, in watts per square meter,

where  $\lambda$  is the latent heat of vaporization, equal to

2,450 joules per gram at 20 °C; and

$E$  is the quantity of water evaporated, in grams per square meter per second.

The climatic, hydrologic, and vegetative conditions in Owens Valley required the use of numerous sites and more than one method to quantify ET there. Seven sites (fig. 1) were selected on the basis of hydrologic conditions and vegetation representative of the valley floor. Continuous data were collected at site C (northern area), site F (central area), and site L (southern area) within the valley for use in the Bowen-ratio and Penman-combination methods. The Bowen-ratio method was used at these sites for as long as 2 weeks each month during the growing season from April 1984 through October 1985. The Penman-combination method was used continuously at the same sites from December 1983 through October 1985. One-half-hour average ET estimates by method and site were summed for 24-hour periods and daily totals were averaged by month to estimate yearly ET. Intermittent measurements were collected at four additional locations (sites A, E, G, and J) using the eddy-correlation method for as long as 24 to 96 hours each month during the growing season from April 1984 through October 1985. Using three methods provided a means to check, calibrate, and correlate the methods and instrumentation, as well as to extrapolate missing or minimal data.

### Bowen-Ratio Method

#### Background and Theory

Bowen (1926) was the first to suggest an equation for determining evaporation from the ratio of sensible-heat flux to latent-heat flux from any surface in terms of the net radiation absorbed and the amount of soil-heat flux stored. Many researchers have since applied the Bowen ratio successfully in energy-budget estimates for a variety of plant communities. Only a partial list of references of others' use of the Bowen-ratio method is discussed in this report. ET from cultivated crops was estimated by Tanner (1960) who demonstrated that the Bowen-ratio method compares closely with lysimeter ET estimates. Storr and others (1970) applied this method to a lodgepole pine forest and concluded that their ET estimates were as accurate as water-balance

ET estimates. Bowen-ratio estimates of ET from a maturing corn crop were made by Wilson and Rouse (1972) and they compared results to equilibrium ET estimates and thus tested their model. Thompson (1974) applied the Bowen-ratio method to three types of rangeland vegetation (grass, pine, and meadow communities) and results were as accurate as water-balance ET estimates. Bowen-ratio estimates over a rangeland stand of saltcedar were made by Gay and Fritschen (1979), their results compared closely to lysimeter ET estimates.

Sensor bias has long been recognized as a source of error when measuring the very shallow thermal and vapor-density gradients used for Bowen-ratio calculations. Interchanging the sensors periodically is one way of eliminating bias. The temperature and vapor-density difference is averaged for several cycles so that each sensor has had equal time at both positions. This averages any offsets that may be present between the sensors. Suomi (1957) may have been the first to eliminate bias by alternating the sensor positions. Since then, Suomi and Tanner (1958), Fritschen (1965), Sargeant and Tanner (1967), and Black and McNaughton (1971) have described designs of apparatus to be used for exchanging Bowen-ratio sensors. Rosenberg and Brown (1974) described one variation where sensors were mounted on a vertical beam at several heights. The beam was switched from the vertical to the horizontal sensor periodically to take readings at an assumed uniform temperature and vapor density. Leppanen (1981) brought the air from different heights to a single psychrometer for which wet- and dry-bulb temperatures were to be measured, thus in effect, using the same sensors to measure air temperature and vapor density at several heights.

In determining the components of an energy budget, net radiation and soil-heat flux can be measured without much difficulty. Sensible- and latent-heat fluxes depend on atmospheric fluctuations and are somewhat more difficult to determine. From the eddy-diffusion theory, the sensible-heat flux (H) is given by the equation:

$$H = K_h \rho_a C_p \frac{dT}{dx}, \quad (2)$$

where  $K_h$  is the eddy-diffusion coefficient for heat transport, in square meters per second;

$\rho_a$  is the corrected air density, in grams per cubic meter, equal to:

$$\rho = \frac{\text{station barometric pressure, in kilopascals}}{\text{sea-level barometric pressure, in kilopascals}} \quad (3)$$

$\rho$  is the air density, equal to 1,204 grams per cubic meter at 20 °C;

$C_p$  is the heat capacity of air, equal to 1.01 joules per gram per degree Celsius; and

$\frac{dT}{dx}$  is the temperature gradient in direction x.

Similarly, the latent-heat flux is given by the equation:

$$\lambda E = K_v \lambda \frac{d\rho_v}{dz}, \quad (4)$$

where  $K_v$  is the eddy-diffusion coefficient for vapor transport, in square meters per second; and

$\frac{d\rho_v}{dz}$  is the vapor-density gradient in direction of flux, in grams per meter to the fourth power.

As shown by Bowen (1926), the ratio of sensible- to latent-heat flux is given by:

$$\beta = \frac{H}{\lambda E} = \frac{K_h \rho_a C_p \frac{dT}{dx}}{K_v \lambda \frac{d\rho_v}{dz}}, \quad (5)$$

where  $\beta$  is the Bowen ratio, dimensionless.

If  $K_h$  is assumed equal to  $K_v$ , and finite-difference approximations of the temperature and vapor-density gradients are used, the equation reduces to:

$$\beta = \gamma \frac{\Delta T}{\Delta \rho_v}, \quad (6)$$

where  $\gamma$  is the psychrometer constant, in grams per cubic meter per degree Celsius;

$T$  is the air temperature in degrees Celsius;

$\Delta T$  is the difference in air temperature at two heights, in degrees Celsius;

$\rho_v$  is the vapor density, in grams per cubic meter; and

$\Delta \rho_v$  is the difference in vapor density at the same two heights used for measuring air temperature, in grams per cubic meter.

The psychrometer constant ( $\gamma$ ) can be calculated by:

$$\gamma = \frac{\rho_a C_p}{\lambda}. \quad (7)$$

Vapor density ( $\rho_v$ ) can be determined by:

$$\rho_v = \rho'_v - \gamma(T - T_w), \quad (8)$$

where  $\rho'_v$  is the saturated vapor density, in grams per cubic meter; and

$T_w$  is the wet-bulb temperature, in degrees Celsius.

One of several equations for calculating saturated vapor density ( $\rho'_v$ ) at the wet-bulb temperature is (Campbell, 1977, p. 22):

$$\rho'_v = \frac{\exp \left[ 52.57633 - \left( \frac{6790.4985}{T_w + 273.15} \right) - 5.02808 \ln(T_w + 273.15) \right]}{R (T_w + 273.15)}, \quad (9)$$

where R is the water vapor specific gas constant equal to  $4.62 \times 10^{-4}$  kilojoules per gram per degree Kelvin.

Manipulation of the energy-budget equation results in an equation for use of the Bowen-ratio method in this study for estimating latent-heat flux:

$$\lambda E = \frac{R_n - G}{1 + \beta}. \quad (10)$$

### Instruments

The instruments used for the Bowen-ratio method at sites C, F, and L (fig. 1) consisted of a modified Fritschen net radiometer, a thermopile-type soil-heat-flux plate, and a pair of ventilated wet- and dry-bulb psychrometers. The data were recorded using a Campbell Scientific Inc.<sup>1</sup> micrologger (model CR-21) that has the capability of recording seven analog and two pulse-counting data channels on cassette tape.

Net radiometer.--Net radiation is the downward flux of solar radiation and longwave radiation minus the upward flux of reflected solar radiation, and longwave radiation between the surface and point of measurement (Fritschen and Gay, 1979). The modified Fritschen net radiometer uses a 22-junction manganin-constantan thermopile in circuit with a temperature-compensated thermistor. A standard radiometer has hemispherical-shaped polyethylene domes 0.15 mm thick and requires pressurization to maintain this shape, whereas the modified unit has heavy-duty self-supporting domes 0.50 mm thick and requires no pressurization. The sensitive surface is blackened and enclosed within the dome. Manufacturer specifications indicate a sensitivity of 5 microvolts per watt per square meter, an internal resistance of 200 ohms, and a time constant of approximately 12 seconds.

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<sup>1</sup>Use of trade names in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

The net radiometer scans a conical area both upward and downward with a field of view of about 65 degrees. Towers, masts, and other objects can cast shadows on either the sensing element or on the area that the downward-directed element is sensing. This is especially true for the angles from east-northeast through south to west-northwest in the northern hemisphere (Fritschen and Gay, 1979).

The manufacturer recommends that the net radiometer be aspirated with dry nitrogen gas to remove any inside condensation that could change the response of the instrument. Both aspirated and nonaspirated net radiometers were used in this study. Minimal condensation was observed in the nonaspirated net radiometers and only during night hours. Further maintenance required that the outer surface of the dome be washed periodically with distilled water and dried with nonabrasive tissue paper in order to remove dirt and dust.

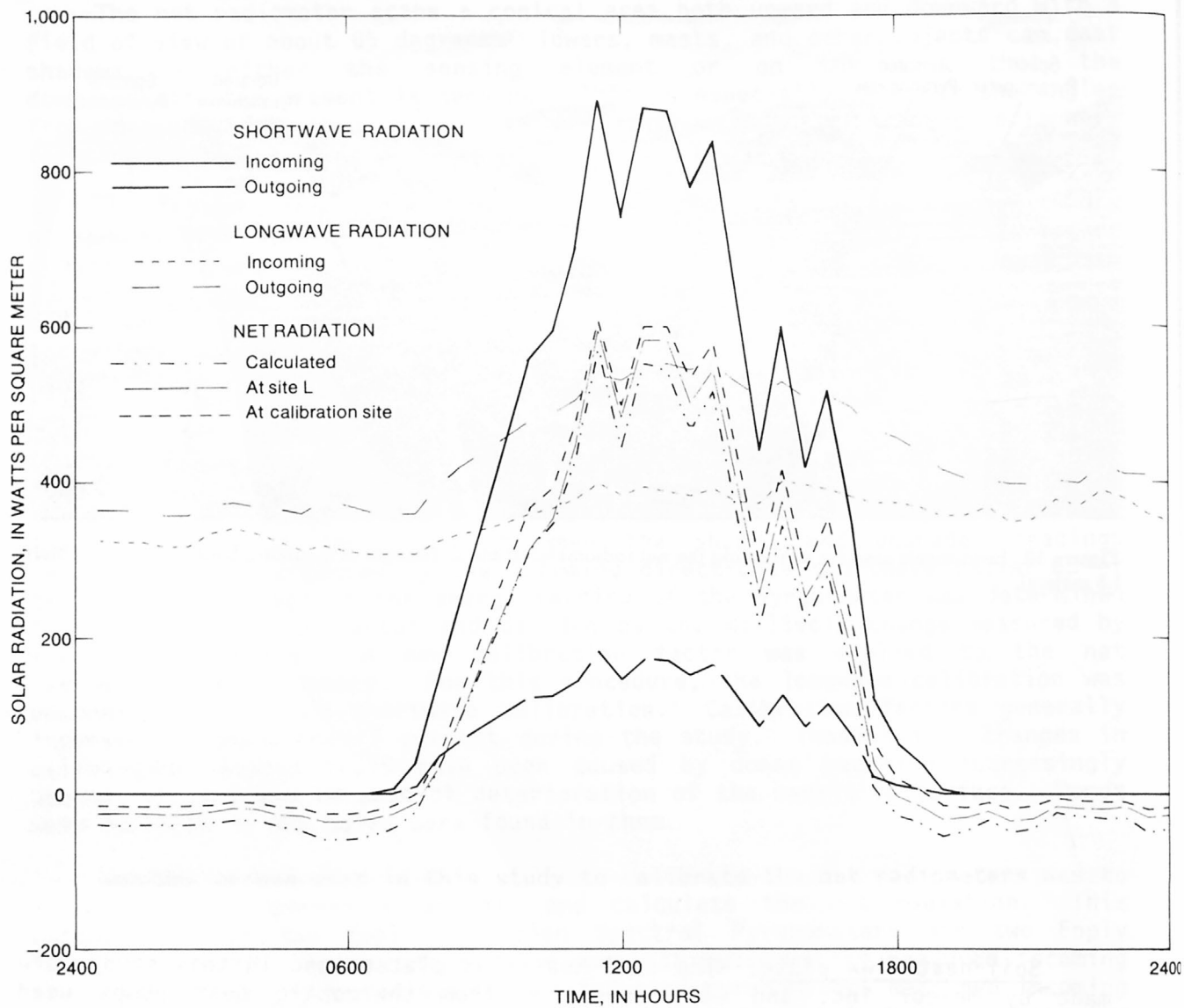
Net radiometers used in this study were calibrated by a shading technique (Fritschen and Gay, 1979). The calibration was done on a clear day at solar noon, when possible, using an Epply Precision Spectral Pyranometer. The instruments were simultaneously shaded to block the direct rays of the sun. The difference in the signal between the shaded and unshaded readings represented that produced by the incoming direct-beam shortwave radiation of the sun. The change in the energy reading of the pyranometer was determined from its calibration factor and divided by the millivolt change measured by the net radiometer. A new calibration factor was applied to the net radiometer, if necessary. For this procedure, the longwave calibration was assumed equal to the shortwave calibration. Calibration factors generally increased no more than 7 percent during the study. These slight changes in calibration factors could have been caused by domes becoming increasingly opaque, or possibly because of deterioration of the sensitive surface. Domes were replaced if any holes were found in them.

Another method used in this study to calibrate the net radiometers was to measure each component separately and calculate the net radiation. This method required two Epply Precision Spectral Pyranometers and two Epply Precision Infrared Pyranometers. The spectral pyranometers measured incoming and outgoing shortwave radiation; the infrared pyranometers measured incoming and outgoing longwave radiation. The mast and setup of instruments used for calibrating the net radiometer is shown in figure 10. This calibration mast was located approximately 50 m south of site L. The results from two net radiometers are compared to the results of the calculated net radiation at the calibration mast on September 18, 1984 (fig. 11). One net radiometer was located on the mast at site L and the other was located on the calibration mast. The measurements of net radiation by the Fritschen net radiometer compare closely with the calculated net radiation. However, the calculated net radiation commonly is less than that measured by the net radiometer.



Figure 10. Instruments used for calibrating the net radiometer at site L. (Length of mounting board is approximately 1.5 meters).

Soil-heat-flux plate.--The soil-heat-flux plates used in this study were made by Melcor Inc. and were developed from thermopile heat pumps used commercially as cooling devices, and are described by Weaver and Campbell (1985). The devices, which were sealed with epoxy, produce millivolt potential from which soil-heat flux can be determined by use of a calibration factor. The plates were individually calibrated in a special chamber built by Harold L. Weaver, U.S. Geological Survey, similar to the one described by Fuchs and Tanner (1968). Weaver and Campbell (1985) determined that the effect of temperature on the calibration constant was larger for these plates than for conventional soil-heat-flux transducers, but was still negligible when compared to other uncertainties in measuring the energy budget. The plates were positioned horizontally beneath a 10-mm layer of undisturbed soil. Sensors were checked for exposure to the atmosphere particularly after high winds. The change in energy storage of the layer of soil above the plates somewhat affects the hourly flux difference. Fuchs and Tanner (1968) showed that, during a 24-hour period, the errors in daily values of soil-heat flux without heat storage corrections were considerably reduced from those determined for hourly data. For this study heat-storage corrections were not used, assuming that error in soil-heat flux and the other terms of the energy budget canceled each other during a 24-hour period.

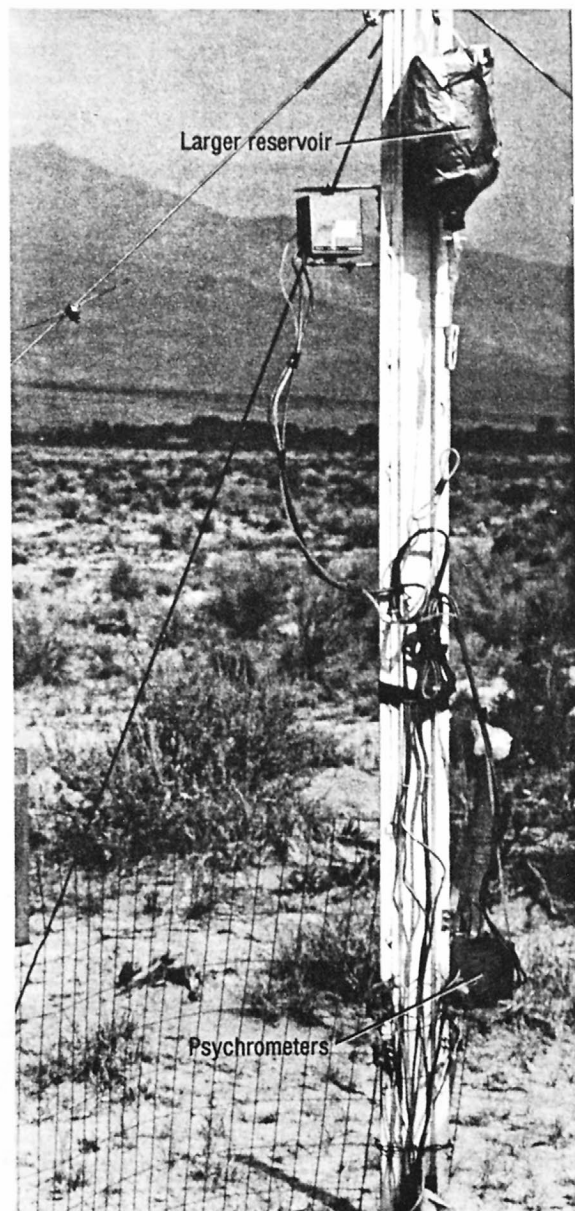


**Figure 11.** Comparison of components of net radiation, calculated net radiation, and measured net radiation at site L, September 18, 1984.

Psychrometer.--Air temperature and vapor-density gradients are generally measured with wet- and dry-bulb psychrometers. Most automated psychrometers used in research are made by hand, and many designs are available. Accurate psychrometers, however, can be exceedingly difficult to build and calibrate. The commercially available psychrometers used in this study were made by the Delta-T Corporation and are ventilated by fans driven by 6-volt direct-current motors. The standard size 20-mm water reservoirs on the model used were inadequate for use in the Owens Valley study because they would be evaporated dry within less than a day during typical hot, dry summer conditions. This problem was corrected by adding a larger reservoir that was used to drip feed the standard reservoir as shown in figure 12.

The psychrometers had two Fenwal Electronics nonlinear thermistors used for measuring the wet- and dry-bulb temperatures. The major error component was the  $\pm 0.2$  °C accuracy. The Campbell Scientific Inc., CR-21 data logger, provided a fifth-order polynomial function specifically regressed for these thermistors.

A psychrometer-exchange method was used to remove systematic errors introduced by thermistor mismatch from the air-temperature and vapor-density vertical gradient measurements. The system required the placement of one psychrometer at the top of the plant canopy (approximately 1 m above ground level) and a second psychrometer 1 m higher. The positions of the psychrometers were alternated every 15 minutes. The exchange was done by a reversible, motor-driven, chain and sprocket assembly which supported the psychrometers (fig. 12). The electronic part of the system included microswitches attached to the mast and a separate interface and motor-drive board, controlled by the data logger. Operation and design of the system was presented by Simpson and Duell (1984).



**Figure 12.** Bowen-ratio psychrometer apparatus at site F. (Mast height is approximately 2.3 meters above land surface.)

At the start of each 15-minute cycle for collecting psychrometer data all power to the system was off. After the first 2 minutes the data logger was programmed to provide an output signal received by the interface and motor-drive control board, activating the exchange motor and exchanging the positions of the psychrometers. After the psychrometers changed position, power to the exchange motor was turned off. Three minutes after the start of each 15-minute cycle, the data logger provided another output signal which was received by the fan interface boards on the psychrometers to activate the fans. After the end of each 15-minute cycle, the data logger turns off all interface and fan motors.

Wet- and dry-bulb temperature averages for each psychrometer were recorded every 5 minutes. The gradient measurements, necessary for calculation of the Bowen ratio, were determined from these 5-minute averages for a 30-minute period. The first 5-minute average of each 15-minute cycling period was not used for the Bowen-ratio calculation, because position change was taking place and complete thermistor aspiration had not occurred. At the respective heights, the second and third 5-minute averages were combined after the psychrometers changed positions with the second and third 5-minute averages in the second 15-minute cycle. Thus, in a 30-minute period, four of the 5-minute averages were used to determine the gradient measurements necessary for the calculation of the Bowen ratio.

All instruments were scanned by the data logger every 10 seconds, and 5-minute averages were computed by the data logger and stored. Therefore, in a 24-hour period 1,850 data points per site were recorded when the Bowen-ratio method was being used. All data were recorded on cassette tape for later transfer to a computer. The data were also recorded, when possible, on a paper printer as backup. Maintenance for the data logger consisted of replacing the batteries and servicing the internal packets of air-drying crystals. Maintenance for the tape recorders consisted of replacing the batteries and cleaning the tape-recorder heads with isopropyl alcohol. Temperature extremes were determined to cause some loss of recorded data.

## Results

Daily ET estimates made by use of the Bowen-ratio method for sites C, F, and L are shown in figure 13. These data were one-half-hour averages summed for a 24-hour period. Occasional adjustment to sunrise, sunset, and nighttime data were made when the one-half-hour average appeared erroneous. Other data generally were not corrected. The adjustment procedure, similar to that used by McNaughton and Black (1973), consisted of interpolating between the before and after one-half-hour average, calculating the hourly ET rate and dividing it, or by estimating and zeroing out the erroneous value. ET estimates were highest at site L and lowest at site F (fig. 13). Daily fluctuations in ET generally are caused by available net radiation and are influenced by the amount of cloud cover. Daily average net radiation at site C is shown in figure 14; similar results were found for sites F and L.

In general, data collected from sunset to sunrise may be considered unimportant because little energy is available. At night, sensible-heat flux is mostly negative over terrestrial surfaces. This heat, and that from soil-heat storage combine to provide the energy for the negative net radiation. Occasionally, a mass of warm, dry air advects over the measurement site, resulting in some downward sensible-heat flux being converted to latent-heat flux. This is a relatively rare occurrence, however, and generally the sensible-heat flux and soil-heat flux provide net radiation. ET studies by Fuchs and Tanner (1970), Black and McNaughton (1971), Grant (1975), and Gay (1980) included only daylight hours in their results.

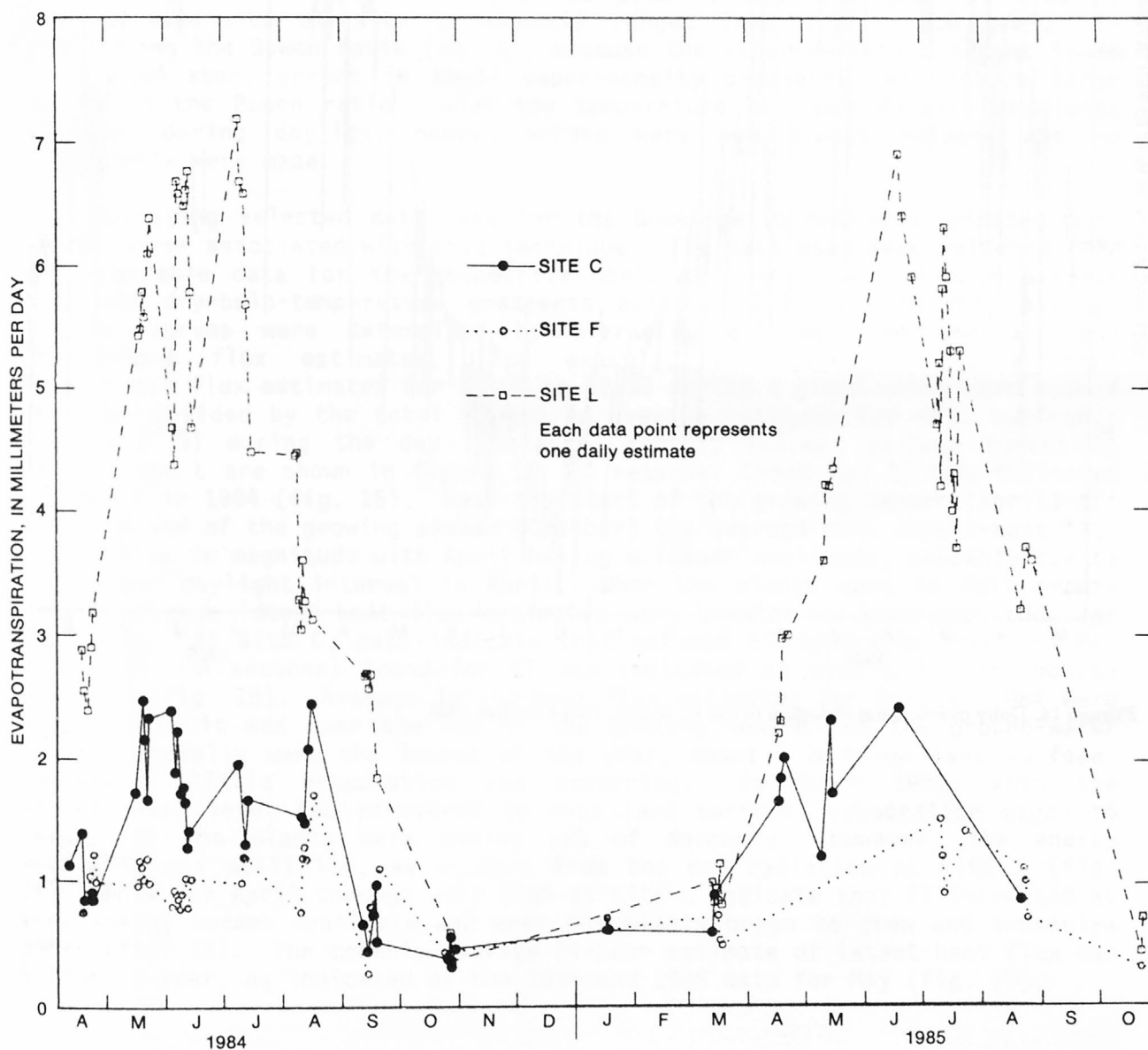
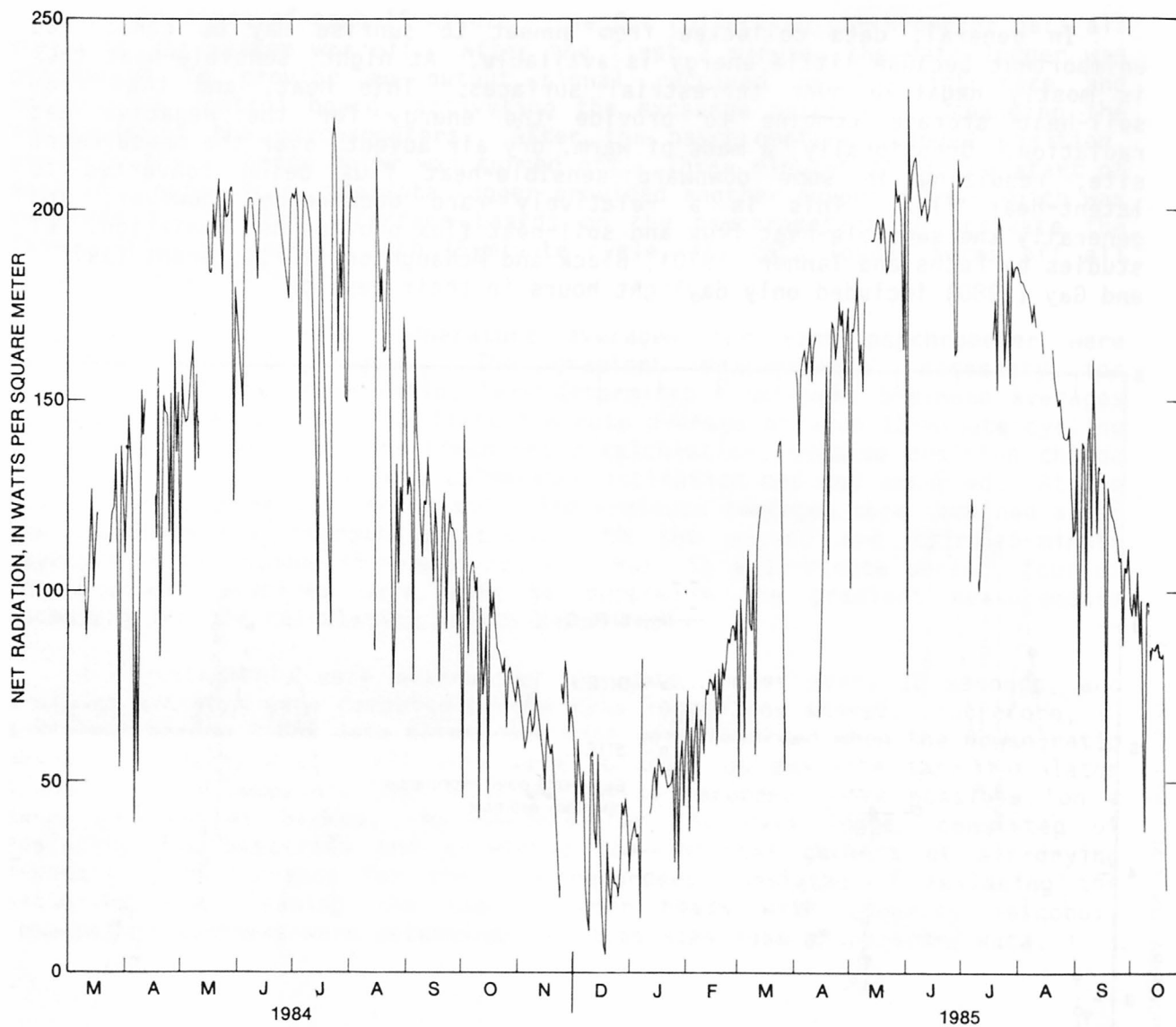


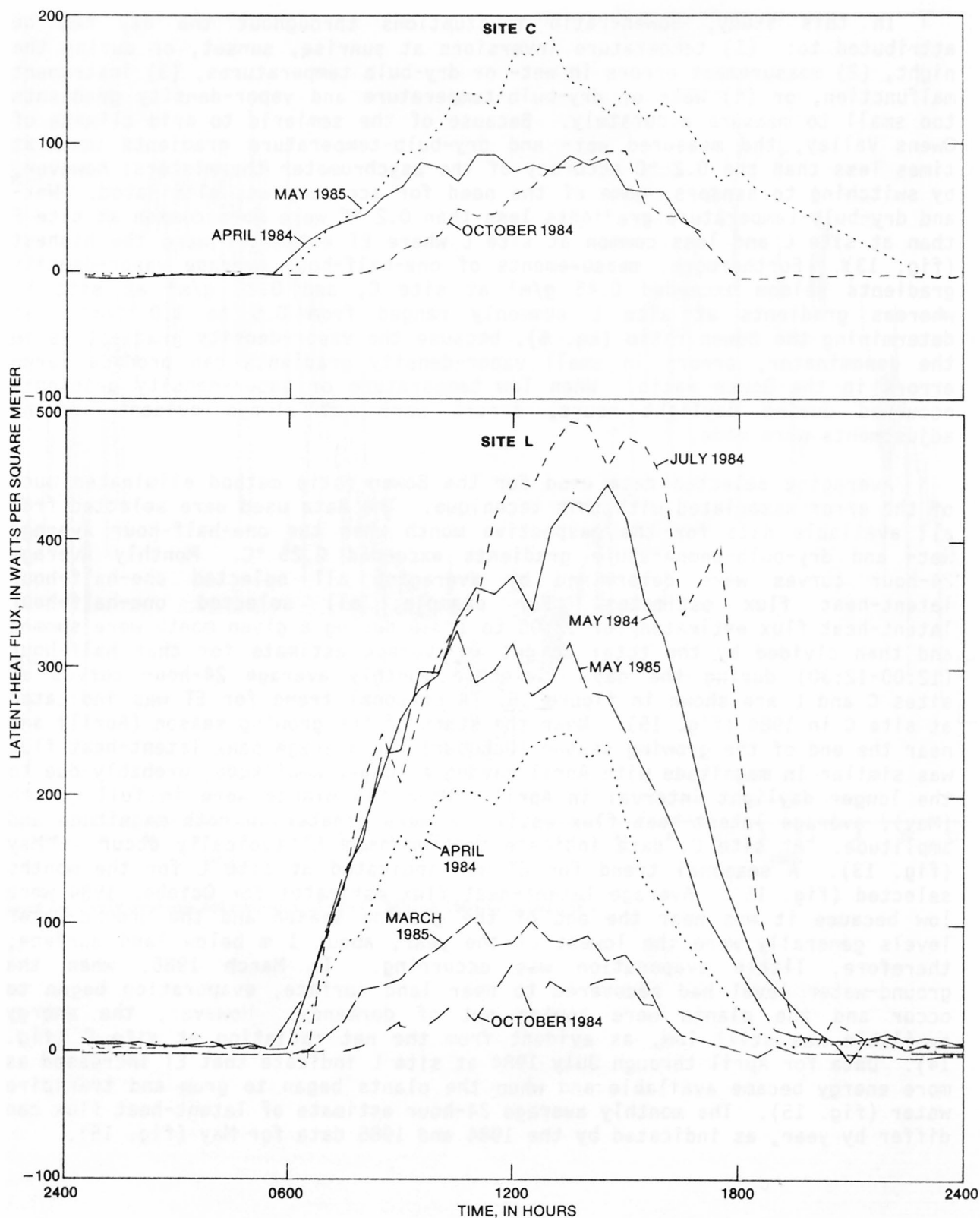
Figure 13. Daily evapotranspiration estimated by the Bowen-ratio method for sites C, F, and L, April 1984-October 1985.



**Figure 14.** Daily average net radiation at site C, March 1984-October 1985.

In this study, Bowen-ratio fluctuations throughout the day may be attributed to: (1) temperature inversions at sunrise, sunset, or during the night, (2) measurement errors in wet- or dry-bulb temperatures, (3) instrument malfunction, or (4) wet- or dry-bulb-temperature and vapor-density gradients too small to measure accurately. Because of the semiarid to arid climate of Owens Valley, the measured wet- and dry-bulb-temperature gradients were at times less than the 0.2 °C accuracy of the psychrometer thermistors; however, by switching to sensors, some of the need for accuracy was eliminated. Wet- and dry-bulb-temperature gradients less than 0.2 °C were more common at site F than at site C and less common at site L where ET estimates were the highest (fig. 13). Furthermore, measurements of one-half-hour average vapor-density gradients seldom exceeded 0.45 g/m<sup>3</sup> at site C, and 0.20 g/m<sup>3</sup> at site F, whereas gradients at site L commonly ranged from 0.5 to 1.0 g/m<sup>3</sup>. In determining the Bowen ratio (eq. 6), because the vapor-density gradient is in the denominator, errors in small vapor-density gradients can produce large errors in the Bowen ratio. When low temperature or vapor-density gradients occurred during daylight hours, errors were not always evident and no adjustments were made.

Averaging selected data used for the Bowen-ratio method eliminated much of the error associated with this technique. The data used were selected from all available data for the respective month when the one-half-hour average wet- and dry-bulb-temperature gradients exceeded 0.25 °C. Monthly average 24-hour curves were determined by averaging all selected one-half-hour latent-heat flux estimates. For example, all selected one-half-hour latent-heat flux estimates for 12:00 to 12:30 during a given month were summed and then divided by the total to get an average estimate for that half-hour (12:00-12:30) during the day. Selected monthly average 24-hour curves at sites C and L are shown in figure 15. A seasonal trend for ET was indicated at site C in 1984 (fig. 15). Near the start of the growing season (April) and near the end of the growing season (October) the average peak latent-heat flux was similar in magnitude with April having a longer amplitude, probably due to the longer daylight interval in April. When the plants were in full growth (May), average latent-heat flux estimates were greater in both magnitude and amplitude. At site C, data indicate that maximum ET typically occur in May (fig. 13). A seasonal trend for ET was indicated at site L for the months selected (fig. 15). Average latent-heat flux estimates for October 1984 were low because it was near the end of the growing season and the ground-water levels generally were the lowest of the year, about 1 m below land surface; therefore, little evaporation was occurring. In March 1985, when the ground-water level had recovered to near land surface, evaporation began to occur and the plants were coming out of dormancy. However, the energy available was still low, as evident from the net radiation at site C (fig. 14). Data for April through July 1984 at site L indicate that ET increased as more energy became available and when the plants began to grow and transpire water (fig. 15). The monthly average 24-hour estimate of latent-heat flux can differ by year, as indicated by the 1984 and 1985 data for May (fig. 15).



**Figure 15.** Comparison of average 24-hour latent-heat flux estimated for selected months by the Bowen-ratio method at sites C and L.

## Eddy-Correlation Method

### Background and Theory

The eddy-correlation method determines the turbulent fluxes of sensible and latent heat from covariances (Brutsaert, 1982). Only a partial list of references by others' use of the eddy-correlation method are presented in this report. Swinbank (1951) was the first to propose an eddy-correlation method to estimate the vertical fluxes of sensible and latent heat that are transported by fluctuations or eddies in the atmosphere. Other researchers include Businger and others (1967), who reported results of a sensible-heat flux comparison experiment for a hay crop, where three different types of instruments were used. Dyer and others (1967) presented a paper describing two instruments that were used in the study by Businger and others (1967). Close agreement was determined by Goltz and others (1970) between eddy-correlation data and two other methods for a snap bean crop. Similar results were determined by Wesely and others (1970) using the same instruments for alfalfa and snap bean crops. McBean (1972) presented data estimating the error in vertical wind sensors. Estimates of sensible- and latent-heat flux were determined for a pine forest by Moore (1977) with use of the eddy-correlation method. The eddy-correlation method was determined to be useful by Spittlehouse and Black (1979) because it does not require measurements of the very small air-temperature and vapor-density gradients necessary for use of the Bowen-ratio method. Daily eddy-correlation data collected in Owens Valley for 1984 have been published in a report by Duell (1985).

The eddy-correlation flux equations have been documented by Priestley (1959), Rosenberg (1974), and Brutsaert (1982). For the eddy-correlation method, latent- and sensible-heat flux were calculated independently of other energy-budget components (net radiation and soil-heat flux). Latent-heat flux was calculated from the covariance of vapor density and vertical windspeed fluctuations and sensible-heat flux was calculated from the covariance of vertical windspeed and air-temperature fluctuations.

Eddy-correlation flux equations are (Campbell, 1977, p. 35):

$$\lambda E = \overline{\rho_v' w'}, \quad (11)$$

and

$$H = \rho_a C_p \overline{w' T'} \quad (12)$$

where  $'$  is the instantaneous deviation from the mean;  
— is the means for a 30-minute period; and  
 $w$  is the vertical wind velocity, in meters per second.

Weeks and others (1987) described in detail the calculations made using instruments manufactured by the Campbell Scientific Inc. for the eddy-correlation method. Theoretically, latent- and sensible-heat flux equal the energy budget (net radiation minus soil-heat flux); however, in field conditions the components did not equal the budget, indicate the need to calculate the difference or closure between the fluxes and the energy budget. The percent closure of the energy budget can be calculated by rearranging equation 1:

$$\text{Energy-budget closure} = \frac{\lambda E + H}{R_n - G} \times 100. \quad (13)$$

An alternative approach to estimating ET also was used in this study. This method was similar to that used by Grant (1975), who estimated evaporation from the energy budget by measuring sensible-heat flux, net radiation, and soil-heat flux. The energy-budget residual used in this study was more accurate than measurements of direct latent-heat flux based on regression analysis of the energy-budget closure, calibration errors associated with the direct-vapor-flux instrument, manufacturer's recommendations, and field tests. Therefore, latent-heat flux was calculated as a residual of the energy-budget by rearranging equation 1:

$$\lambda E = R_n - G - H. \quad (14)$$

Both estimates of ET (based on direct and on residual latent-heat flux as determined by the eddy-correlation method) were used in this study.

### Instruments

The instruments used for the eddy-correlation method at sites A, E, G, and J (fig. 1) are part of a mobile system that includes a Lyman-alpha hygrometer, a sonic anemometer, a fine-wire thermocouple, and a CR-7 data logger. The instruments, except for the data logger, are shown in figure 16. This equipment collects and processes aerodynamic data in real time. In this study, the energy budget was simultaneously measured at these sites by using a net radiometer and soil-heat-flux plate described above.

Lyman-alpha hygrometer.--The Lyman-alpha hygrometer measures vapor density on the basis of the principle that water vapor strongly absorbs energy at the Lyman-alpha wavelength of ultraviolet light. The source of the Lyman-alpha radiation is a partially evacuated tube that contains a small amount of hydrogen gas energized with a high-voltage electrostatic field. The adjacent detector tube, which contains nitric oxide, senses the strength of the incoming Lyman-alpha radiation. The relative attenuation of the Lyman-alpha signal is proportional to the water-vapor density between the Lyman-alpha source and the detector (Buck, 1976). Field maintenance required replacing the source tube after the first year and replacing the detector tube after approximately 200 hours of use.

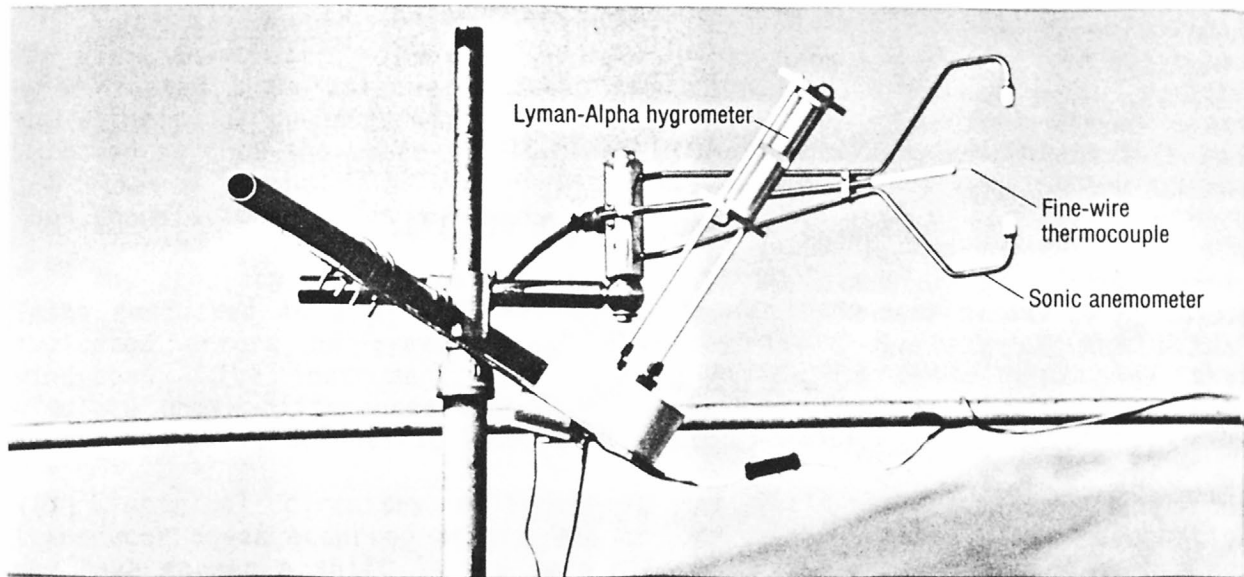


Figure 16. Eddy-correlation instruments. (Height approximately 3 meters above land surface.)

The Lyman-alpha hygrometer provides a measure of water-vapor-density fluctuations. However, because the Lyman-alpha source strength drifts with time, the instrument is not considered accurate for absolute vapor-density measurements. By collecting covariances over a relatively short period (5 minutes), the effects of long-term drift are eliminated. The Lyman-alpha hygrometer was not factory calibrated.

The Lyman-alpha hygrometer works on a light-attenuation principle, which follows Beer's law:

$$\frac{V}{V_0} = e^{-Kx\rho_v}, \quad (15)$$

where  $V$  is the hygrometer voltage output, in millivolts;

$V_0$  is the unattenuated voltage output, in millivolts;

$K$  is the an attenuation coefficient, in square meters per gram; and

$x$  is the path length, in meters.

If  $x$  is a constant, so that  $Kx$  is a lumped parameter, and  $K$  depends on  $\rho_v$  in the simplest nonconstant way, then:

$$Kx = A + B\rho_v, \quad (16)$$

where  $A$  and  $B$  are experimentally determined coefficients. Substituting equation 16 into equation 15:

$$\frac{V}{V_0} = e^{-(A + B\rho_v)\rho_v}. \quad (17)$$

Upon taking the logarithm of both sides and rearranging:

$$\ln V = \ln V_0 - A\rho_V - B(\rho_V)^2. \quad (18)$$

Then differentiating equation 18 with respect to V:

$$\frac{d}{dV} (\ln V) = \frac{d}{dV} [\ln V_0 - A\rho_V - B(\rho_V)^2],$$

where  $\frac{d}{dV}$  is the voltage gradient, which reduces to

$$-\frac{1}{V} = A \frac{d\rho_V}{dV} + 2 B\rho_V \frac{d\rho_V}{dV}$$

or

$$-\frac{1}{V} = \frac{d\rho_V}{dV} (A + 2B\rho_V), \quad (19)$$

where  $\frac{d\rho_V}{dV}$  is the vapor-density voltage gradient.

Solving equation 19 for  $\frac{d\rho_V}{dV}$

$$\frac{d\rho_V}{dV} = \frac{-1}{V(A + 2B\rho_V)}. \quad (20)$$

Readings of the data logger are converted to latent-heat flux, in watts per square meter, by multiplying the data (eq. 20) by 2,450 J/g, the latent heat of vaporization at 20 °C. Because vapor density is in equation 20, a measure of the absolute value of vapor density is needed, requiring a separate instrument. Repeated check calculations were made for this study adjusting the latent-heat flux multiplied by the current vapor density determined from a Delta-T psychrometer. It was determined that the change in vapor density did not result in a substantial change in the latent-heat-flux multiplier. Thus, the multiplier selected at the time each measurement began was adequate in all cases. These multipliers were calculated by measuring the vapor density with an Assman psychrometer.

The Lyman-alpha hygrometer was calibrated by placing it in a humidity chamber that duplicates known ranges of on-site vapor densities. A recording psychrometer was placed within the chamber, and the air vapor was circulated to maintain a homogeneous mixture. In general, the calibration coefficients (A and B, eq. 20) remain stable for at least 1 year on most Lyman-alpha detector tubes (B.D. Tanner, Campbell Scientific Inc., oral commun., 1984).

Sonic anemometer.--Fluctuations in vertical windspeed are measured with the sonic anemometer. The sonic anemometer measures the phase shift generated by convected translation of emitted soundwaves caused by the wind. Because the velocity of sound is affected by temperature, the acoustic transducers are switched so that the upper and lower units alternate as emitters and receivers 160 times a second. The net phase shift, determined by summing the up and down translations, gives a measure of the windspeed alone.

The accuracy of the sonic anemometer can be determined in a wind tunnel. Tests conducted in a wind tunnel by the manufacturer for three instruments indicated errors no greater than approximately 5 percent of the actual windspeed. The instruments are factory calibrated using test jigs that simulate phase differences corresponding to windspeeds of 0 and 4 m/s (B.D. Tanner, Campbell Scientific Inc., oral commun., 1984).

Electrical circuitry malfunctions and accidental deformation of the transducer domes occurred at the end of 1984 field season. This deformation may have caused a shift in the zero offset reading for the sonic anemometer, but did not affect the slope of the relation between windspeed and voltage output. This offset shift has no effect on computed eddy-correlation fluxes because those fluxes depend only on fluctuation about the mean. However, too severe a shift can cause one-sided truncation of the signal. Therefore, the anemometer was redesigned following the 1984 season to use replaceable transducers.

Fine-wire thermocouple.--Fluctuations in air temperature are measured with a fine-wire (12.7  $\mu\text{m}$  in diameter) Chromel-Constantan thermocouple that has a rapid response time. Physically, the thermocouple is plugged into the mount of the sonic anemometer. The reference junction for the fine-wire thermocouple is located in the sonic anemometer stand. Owing to the small diameter of the thermocouple wire, damage to the weld junction was common. The weld junction was separated several times by windblown sand, precipitation, and spider webs. Replacement thermocouples were standard field equipment.

Data logger.--The data logger used for the eddy-correlation method was a Campbell Scientific Inc. model CR-7. The eddy-correlation instruments were scanned every 0.1 second for millivolt potential. Mathematical algorithms stored in the data logger computed the means and covariances of the voltage from each instrument and stored the data over subintervals of 5 minutes. This subinterval was chosen to avoid the effects of long-term drift or trends in vapor density, vertical windspeed, and air temperature on computed eddy-correlation fluxes. The 5-minute subinterval values were accumulated within the data logger for 30-minute periods and then converted to actual readings in watts per square meter by the use of the appropriate multiplier. Calibration to absolute values with the eddy-correlation instruments was not as important as the ability of the system to measure and track rapidly changing vapor-density, vertical windspeed, and air-temperature fluxes accurately. However, because of the nonlinearity of the Lyman-alpha-hygrometer calibration with vapor density, a value of actual vapor density is needed from another instrument each time the method was used.

## Results

ET estimates were collected for a total of 24 to 96 hours each month during the growing season at sites A, E, G, and J by use of the eddy-correlation method. Daily ET estimates were sums of one-half-hour averages during a 24-hour period. All 24-hour periods were averaged by month and site; no adjustments were made to these data. The monthly average direct and residual ET estimates by the eddy-correlation method for available data at sites A, E, G, and J are shown in figure 17. Direct ET estimates were determined to be lower in all cases than residual estimates. These data indicate that direct ET represents minimum estimates while residual ET represents maximum estimates. Daily estimates of direct ET were not used in this study when the Lyman-alpha hygrometer appeared to be malfunctioning; therefore, less data were available for this method than for the residual method. ET estimates generally increased from April through June or August during the 1984 and 1985 growing seasons at sites A, G, and J (fig. 17). ET estimates were greater at the beginning of the growing season at site E (fig. 17) and then decreased through the season, except for August 1985. The seasonal distribution of ET at site E may indicate that the plants there get most of their water from soil water, rather than ground water. At the beginning of the growing season, the upper soil-water content was high owing to winter precipitation. Through the growing season the plants' transpiration rate and soil evaporation would decline as soil water is depleted. The increase for August 1985 ET estimates at sites E and G may represent ET from soil water accumulated by the large amount of precipitation during July 1985 (fig. 3).

### Penman-Combination Method

#### Background and Theory

Estimates of potential ET can be used to interpolate estimates for actual ET when other measurements are not available. Only a partial listing of references by others' use of the Penman-combination method are presented in this report. Penman (1948) was the first to develop a combination equation to determine evaporation from open water, bare soil, and grass. Potential transpiration as defined by Penman (1956) is a transpiration rate for a short green crop cover that completely shades the ground and never is short of water. Tanner and Pelton (1960) determined that for their use of the Penman-combination method for an alfalfa crop, a wind function that accounts for surface roughness was necessary. The same principles were applied by Van Bavel (1966) in an arid climate with equal results for reaches of open water, wet bare soil, and irrigated alfalfa. Cuenca and Nicholson (1982) stressed the importance of the use of wind-function coefficients consistent with the method of computing the vapor-pressure deficit.

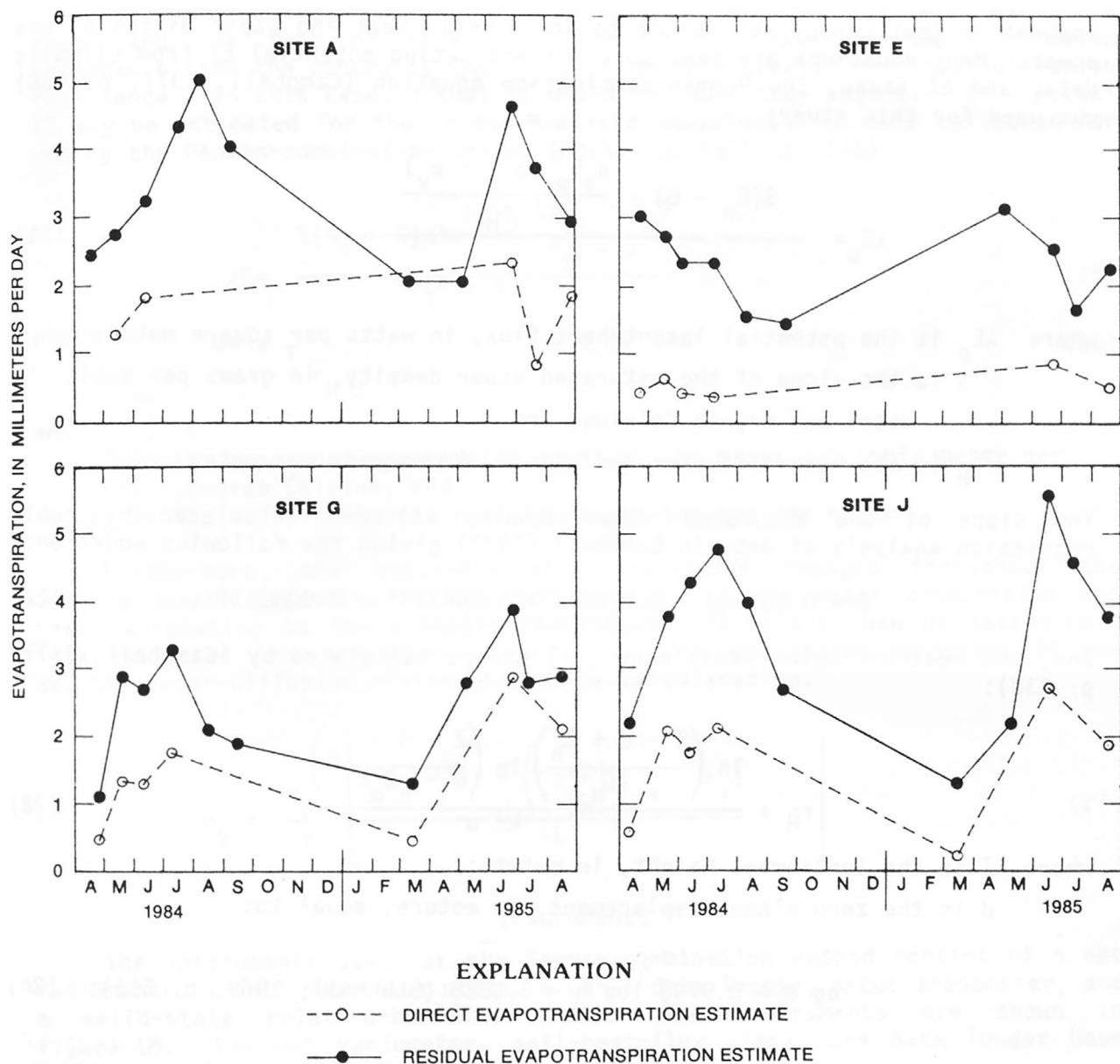


Figure 17. Monthly average direct and residual evapotranspiration estimated by the eddy-correlation method at sites A, E, G, and J, April 1984-August 1985.

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, and of these, the Penman-combination equation (Campbell, 1977, p. 138) was used for this study:

$$\lambda E_p = \frac{S(R_n - G) + \frac{\rho_a C_p (\rho'_v - \rho_v)}{r_H}}{\gamma + S} \quad (21)$$

where  $\lambda E_p$  is the potential latent-heat flux, in watts per square meter;  
 $S$  is the slope of the saturated vapor density, in grams per cubic meter per degree Celsius; and  
 $r_H$  is the heat-diffusion resistance, in seconds per meter.

The slope of the saturated vapor density ( $S$ ) was calculated by cubic regression analysis of data in Campbell (1977) giving the following equation:

$$S = 0.337569 + 0.02067T + 0.00427T^2 + 0.000011T^3, \quad (22)$$

and, the heat-diffusion resistance ( $r_H$ ) can be calculated by (Campbell, 1977, p. 138):

$$r_H = \frac{\ln \left( \frac{Z - d + Z_h}{Z_h} \right) \ln \left( \frac{Z - d + Z_m}{Z_m} \right)}{k^2 u}, \quad (23)$$

where  $Z$  is the instrument height, in meters;  
 $d$  is the zero plane displacement, in meters, equal to:

$$\log d = 0.9793 \log h - 0.1536 \quad (\text{Stanhill, 1969, p. 513}); \quad (24)$$

$h$  is the average crop height, in meters, multiplied by the percentage of vegetation cover;

$Z_m$  is 0.13  $h$ , in meters;

$Z_h$  is 0.2  $Z_m$ , in meters;

$k$  is Von Karman's constant equal to 0.4, dimensionless; and

$u$  is the mean windspeed at height  $Z$ , in meters per second.

It appears likely, in the semiarid to arid Owens Valley, that incomplete cover and the type of vegetation combine to make the vapor-diffusion resistance from the canopy to the air considerably greater than heat-diffusion resistance. In this case, actual ET would be lower than potential ET. Actual ET may be estimated for the Penman-Montieth equations from data collected for use by the Penman-combination method (Montieth, 1973, p. 175):

$$\lambda E = \frac{S(R_n - G) + \frac{\rho_a C_p (\rho'_v - \rho_v)}{r_H}}{\gamma^* + S} \quad (25)$$

where

$$\gamma^* = \gamma \frac{r_v}{r_H}, \quad (26)$$

and

$\gamma^*$  is the apparent psychrometer constant, in grams per cubic meter per degree Celsius; and

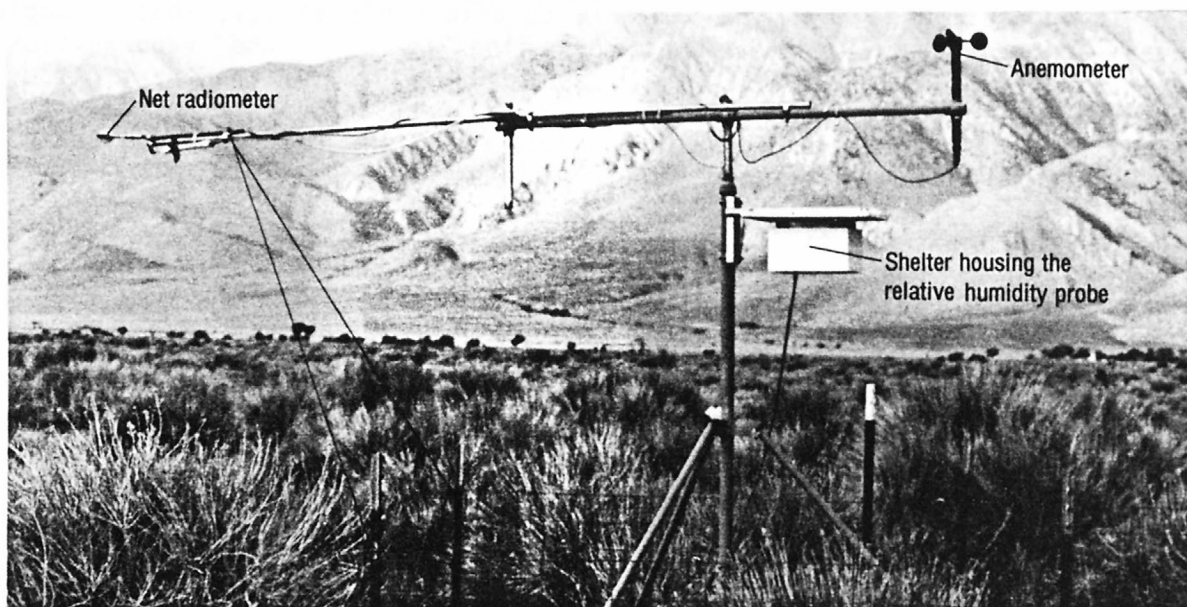
$r_v$  is the vapor-diffusion resistance, in seconds per meter.

Furthermore, the vapor-diffusion resistance changes throughout the growing season depending on the growth stage of the plant communities and their adaptation to the climatic conditions. Therefore, use of latent-heat flux estimated from the Bowen-ratio method and rearranging equations 25 and 26, the vapor-diffusion resistance can be calculated by:

$$r_v = \frac{r_H}{\gamma} \left[ \frac{S(R_n - G) + \left( \frac{\rho_a C_p}{r_H} \right) (\rho'_v - \rho_v)}{\lambda E} - S \right] \quad (27)$$

### Instruments

The instruments used for the Penman-combination method consist of a net radiometer, a soil-heat-flux plate, a CR-21 data logger, a cup anemometer, and a solid-state relative-humidity probe. The instruments are shown in figure 18. The net radiometer, soil-heat-flux plate, and data logger have been described above.



**Figure 18.** Penman-combination instruments at site C. (Approximate height of net radiometer is 2 meters above land surface.)

Anemometer.--The cup anemometer is a three-cup, low-friction device that measures windspeed. Magnetic reed switches measure rotation of the cups, and the switch closures are sensed by the fast pulse-counting channel in the CR-21 data logger. The anemometers used in this study were replaced yearly even though malfunctions did not occur with these instruments in the field.

Relative humidity probe.--Relative humidity was measured by a sulfonated-polystyrene, carbon-electrode element in a probe that changed resistance in proportion to the change in relative humidity. The relative-humidity probe also contained a thermistor that was used as a temperature compensator for vapor-pressure measurements and for recording average air temperatures. Vapor pressure is related to vapor density by the perfect gas law; therefore, vapor density ( $\rho_v$ ) can be calculated by the following equation (Campbell, 1977, p. 22):

$$\rho_v = \frac{P}{R(T + 273.15)}, \quad (28)$$

where P is vapor pressure, in kilopascals.

A mathematical algorithm stored in the data logger was used to calculate the vapor-pressure deficit. Vapor-pressure deficit, the difference between saturated vapor pressure and measured vapor pressure, can be converted to vapor-density deficit by use of equation 28 or calculated directly by use of equation 29.

$$\rho_{vd} = \rho'_v - \rho_v \quad (29)$$

where  $\rho_{vd}$  is the vapor-density deficit, in grams per cubic meter.

Field checks showed that the vapor-density deficit as determined with the relative-humidity probe, compared closely with measurements made by the Delta-T and Assman psychrometers. The resistance element of the relative humidity probe deteriorated with time and from contact with moisture; this element was replaced yearly. The relative-humidity probe was supplied with a radiation shield for protection from solar radiation and precipitation.

Supplemental equipment.--Additional instruments, such as pyranometers and rain gages, were used in the study but the data were not used directly as input for the calculations. A Li-Cor silicon pyranometer was used to measure incoming shortwave radiation and to verify the net radiation measurements. Changes that occurred to net-radiation data typically also occur to solar-radiation data, such as cloud cover masking incoming radiation. Tipping-bucket and storage rain gages were used to collect precipitation data that could be used with water-level data to check the long-term ET predictions from current modeling studies being conducted by others.

The pyranometer used in this study was a nonthermal type that uses a silicon photocell. This type of pyranometer is most sensitive to the visible light spectrum (400 to 700 nm). The pyranometer was checked by comparing it to a spectral pyranometer during daylight hours. The initial calibration of this instrument remained constant throughout the study, and there were no field malfunctions.

The recording rain gages were tipping-bucket types that have microswitches that close each time 0.25 mm of rain accumulates in the collecting buckets. Malfunctioning rain gages were returned to the manufacturer for recalibration. To assure accuracy of the precipitation data, these devices were protected from obstructions that could deflect wind-carried precipitation. The accumulation and melting of snow in the collecting orifice caused errors in the data.

Storage rain gages were used as an additional method of collecting precipitation data. To avoid evaporation, motor oil was added to the gages. Antifreeze was added to the gages in winter months to prevent damage from freezing. Errors in measurements may have occurred when storm events exceeded the 25-mm capacity of the storage reservoirs or when insects became trapped in the layer of oil.

All instruments were scanned every 10 seconds, and 30-minute averages were computed in the data logger and stored. All data were recorded on cassette tape for later transfer to a computer.

## Results

Large potential-ET estimates were determined for sites C, F, and L by use of equation 21. These data were unusually high, mostly a factor of five to ten times the estimates obtained by using the Bowen-ratio method. At site L potential-ET estimates by use of equation 21 were determined to agree with actual ET estimates for a few days in May and June of 1984 and 1985. Duell and Nork (1985) compared in detail the potential-ET estimates to actual-ET estimates by use of both the Bowen-ratio and eddy-correlation methods in Owens Valley.

The high estimates of potential ET determined from this study may have been caused by high windspeeds (fig. 6) and large vapor-density deficits that are normal in Owens Valley. McNaughton and Black (1973) determined that the meteorological factor most directly controlling forest ET was vapor-density deficit. Furthermore, errors associated with vapor-density-deficit calculations could also have been responsible for the large potential-ET estimates. However, no error was indicated in this measurement because variance analysis of the vapor-density deficit determined with the relative-humidity probe, compared with that calculated from Delta-T psychrometer data, indicated no significant difference between the two methods of data collection. Daily average vapor-density deficits at site F are shown in figure 19. Vapor-density deficits were highest during summer months when vapor densities were low and saturated vapor densities were high owing to high air temperatures. High and low amplitudes in the graph indicate the effect of storms and cooling from cloud cover on vapor-density-deficit data.

The Penman-combination method was modified by continued recalibration of the apparent psychrometer constant ( $\gamma^*$  of eq. 25) to account for differences between heat- and vapor-diffusion resistance. The modification procedure was necessary because of the climatic and vegetation characteristics typical of the Owens Valley. Estimates of plant transpiration made by Groeneveld and others (1986) when compared to estimates of ET by the Bowen-ratio and eddy-correlation methods indicate that the major component of ET in the valley is transpiration from the plants. For plants, water vapor escapes only through the leaf stomata, while the transfer of heat occurs from the entire canopy surface. If much of the surface is dry bare soil, then a much larger surface is available for heat diffusion than vapor diffusion per unit of land area, and heat-diffusion resistance will be less than vapor-diffusion resistance. Also, many plants are adapted to close leaf stomata at night, probably to conserve water. Groeneveld and others (1986) studied five of the common plant species in the valley and determined that stomata typically close near sunset and open near sunrise. Plants may also close stomata during periods of soil-water stress resulting in heat-diffusion resistance being less than vapor-diffusion resistance. During this study in all cases at sites C and F heat-diffusion resistance was determined to be less than vapor-diffusion resistance. The same relation was determined for site L most of the time, except for a few days in May and June 1984-85 when heat- and vapor-diffusion resistance were determined to be equal. For those days, estimates of potential and actual ET were determined to be equal. Estimates of the average one-half-hour heat-diffusion resistance in seconds per meter ranged from 15 to 121 at site C, 17 to 160 at site F, and 18 to 333 at site L.

Hughes (1972) used a Penman-Montieth approach to compare lysimeter-measured ET from saltcedar with that estimated by the Penman-combination equation. He determined stomatal resistance to be a function of windspeed and air temperature, which normally show a diurnal trend. For this study no diurnal trend was indicated for vapor-diffusion resistance and no correlations were determined with any of the measured meteorological data used in equation 27.

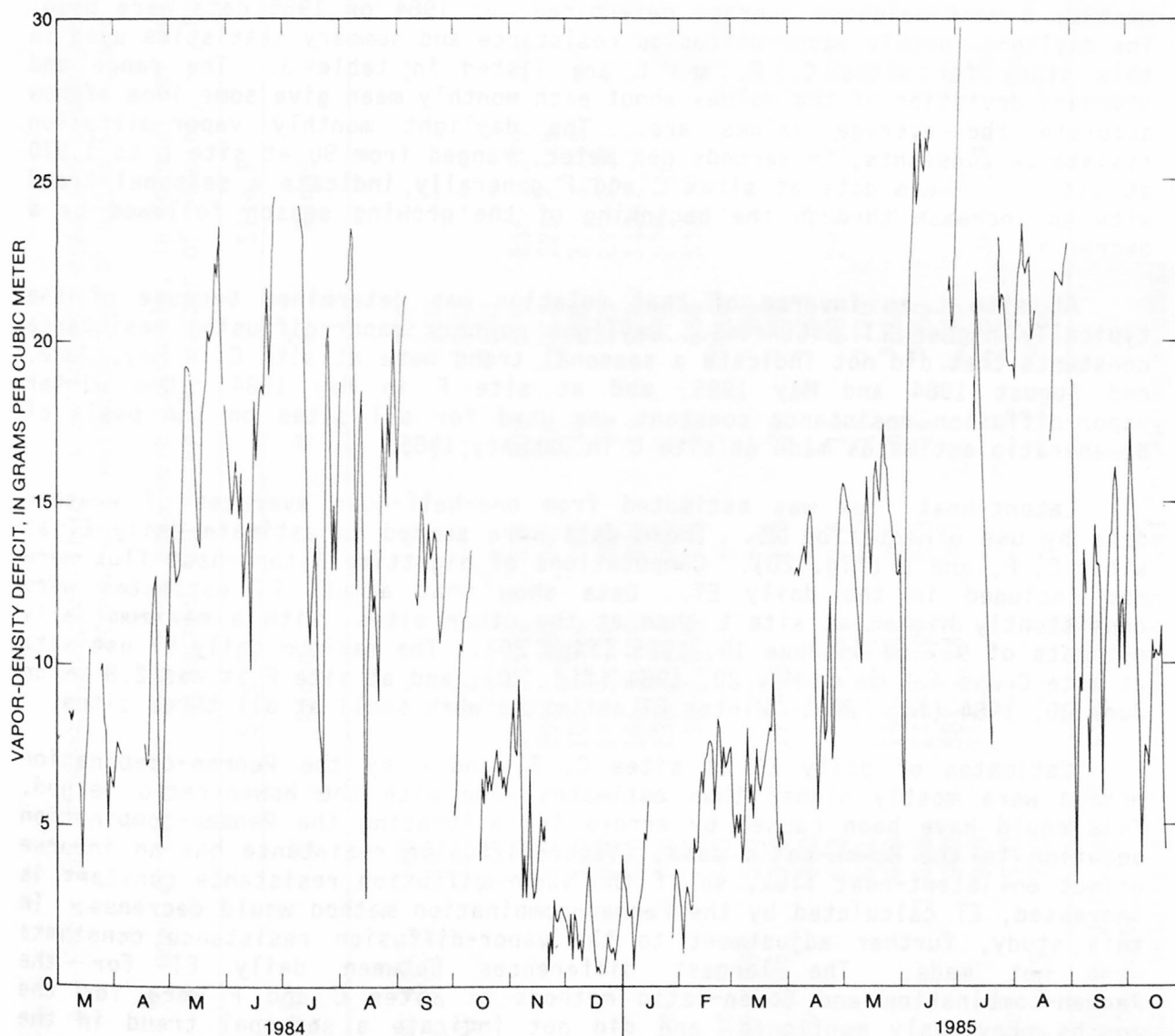


Figure 19. Daily average vapor-density deficit at site F, March 1984-October 1985.

Latent-heat flux estimated by the Bowen-ratio method provides a means of estimating vapor-diffusion resistance (eq. 27). For this procedure, daylight and nighttime data were treated separately; only data in which the average one-half-hour wet- and dry-bulb-temperature gradients exceeded 0.25 °C were used. Occasionally at night one-half-hour negative vapor-diffusion resistances were indicated. However, there is no physical significance to negative vapor-diffusion resistance and this can only arise due to data errors. An examination of equation 27 indicates that such negative numbers were determined when the net radiation was too negative or the upward soil-heat flux was underestimated. Under these conditions a negative latent-heat flux and thus a negative vapor-diffusion resistance would be indicated. For this reason nighttime latent-heat flux was not included in the daily total ET as calculated by the Penman-combination method. A monthly average estimate of the daylight vapor-diffusion resistance constant was determined for each site and incomplete data were either estimated for winter months, a mean-weighted average determined, or 1984 or 1985 data were used. The daylight monthly vapor-diffusion resistance and summary statistics used in this study for sites C, F, and L are listed in table 3. The range and standard deviation of the values about each monthly mean give some idea of how accurate the average values are. The daylight monthly vapor-diffusion resistance constants, in seconds per meter, ranged from 90 at site L to 1,070 at site F. These data at sites C and F generally indicate a seasonal trend with an increase through the beginning of the growing season followed by a decrease.

At site L an inverse of that relation was determined because of the typically higher ET estimates. Daylight monthly vapor-diffusion resistance constants that did not indicate a seasonal trend were at site C in May, June, and August 1984 and May 1985, and at site F in May 1984. One winter vapor-diffusion resistance constant was used for all sites on the basis of Bowen-ratio estimates made at site C in January 1985.

Latent-heat flux was estimated from one-half-hour averages of weather data by use of equation 25. These data were summed to estimate daily ET at sites C, F, and L (fig. 20). Computations of nighttime latent-heat flux were not included in the daily ET. Data show that actual ET estimates were consistently higher at site L than at the other sites, with a maximum daily estimate of 9.7 mm on June 19, 1985 (fig. 20). The maximum daily ET estimate at site C was 4.1 mm on May 20, 1984 (fig. 20), and at site F it was 2.8 mm on June 26, 1984 (fig. 20). Winter ET estimates were small at all three sites.

Estimates of daily ET at sites C, F, and L by the Penman-combination method were mostly higher than estimates made with the Bowen-ratio method. This could have been caused by errors in calibrating the Penman-combination equation to the Bowen-ratio data. Vapor-diffusion resistance has an inverse effect on latent-heat flux, so if the vapor-diffusion resistance constant is increased, ET calculated by the Penman-combination method would decrease. In this study, further adjustment to the vapor-diffusion resistance constants were not made. The largest differences between daily ET for the Penman-combination and Bowen-ratio methods at sites C and F were for the months previously mentioned, and did not indicate a seasonal trend in the vapor-diffusion resistance constant. The errors in calibrating the Penman-combination method did not appear to be caused by use of Bowen-ratio data collected during atypical weather conditions.

Table 3.--Estimates of monthly vapor-diffusion resistance used and summary statistics of available data for the Penman-combination method at sites C, F, and L

[ $\bar{X}$ , mean or estimate used if no data were available, in seconds per meter;  $\sigma$ , standard deviation, in seconds per meter; N, number of samples; --, no data]

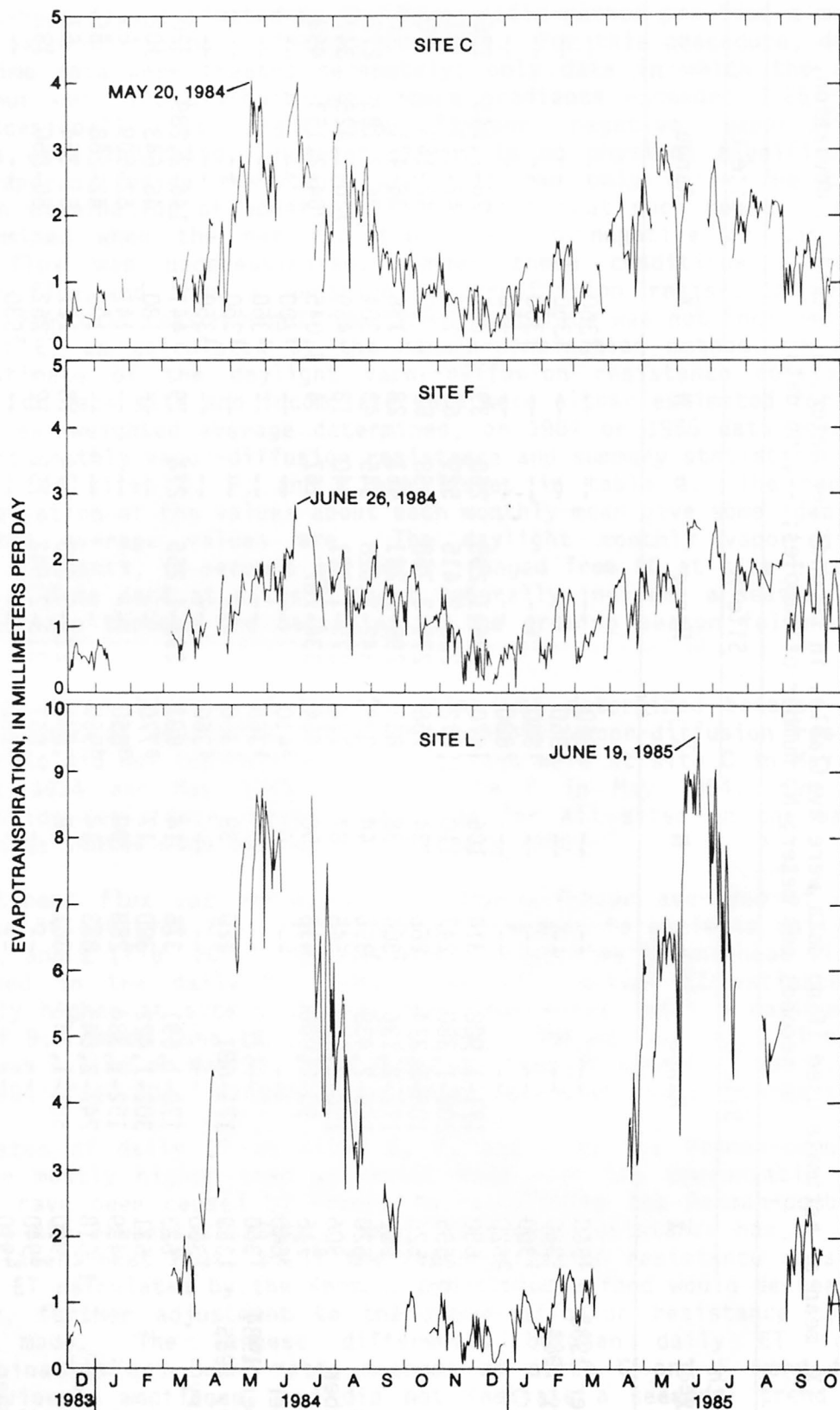
Month and year	Site C				Site F				Site L			
	$\bar{X}$	Range	$\sigma$	N	$\bar{X}$	Range	$\sigma$	N	$\bar{X}$	Range	$\sigma$	N
December 1983	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
January 1984	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
February	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
March	<sup>2</sup> 620	--	--	--	<sup>2</sup> 680	--	--	--	<sup>2</sup> 440	--	--	--
April	650	171-1,922	314	106	670	236-1,295	260	39	205	78-1,145	156	69
May	535	209-1,380	247	110	<sup>1</sup> ,072	225-2,415	529	60	120	47-267	51	86
June	526	108-1,314	266	134	768	271-3,768	498	82	90	42-165	30	76
July	902	172-2,136	504	38	853	299-2,241	463	28	138	36-471	78	69
August	520	166-2,439	396	44	978	342-2,628	545	43	304	76-2,183	272	87
September	906	138-2,254	545	87	778	275-1,821	440	18	459	120-1,425	347	58
October	716	90-2,000	416	58	464	334-707	167	4	<sup>1</sup> ,045	304-2,153	490	37
November	<sup>3</sup> 540	--	--	--	<sup>3</sup> 410	--	--	--	<sup>3</sup> 700	--	--	--
December 1984	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
January 1985	<sup>1</sup> 359	171-681	120	39	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
February	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--	<sup>1</sup> 360	--	--	--
March	623	170-1,591	376	14	681	291-1,256	278	19	441	146-2,289	320	69
April	631	302-1,422	300	17	<sup>3</sup> 770	--	--	--	180	46-643	102	87
May	499	152-1,384	258	40	<sup>3</sup> 860	--	--	--	141	62-509	63	76
June	<sup>1</sup> ,018	247-2,843	853	14	<sup>3</sup> 950	--	--	--	105	42-268	55	32
July	990	581-1,743	361	8	<sup>1</sup> ,043	221-3,093	674	18	127	61-354	57	98
August	<sup>3</sup> 940	--	--	--	<sup>1</sup> ,057	313-2,642	751	12	262	50-860	132	44
September	<sup>4</sup> 910	--	--	--	<sup>4</sup> 780	--	--	--	<sup>3</sup> 530	--	--	--
October 1985	<sup>4</sup> 720	--	--	--	<sup>4</sup> 460	--	--	--	702	325-1,605	327	22

<sup>1</sup>Winter data for all sites.

<sup>2</sup>1985 data.

<sup>3</sup>Data interpolated from preceding and following months.

<sup>4</sup>1984 data.



**Figure 20.** Daily actual evapotranspiration estimated by the Penman-combination method at sites C, F, and L, December 1983-October 1985.

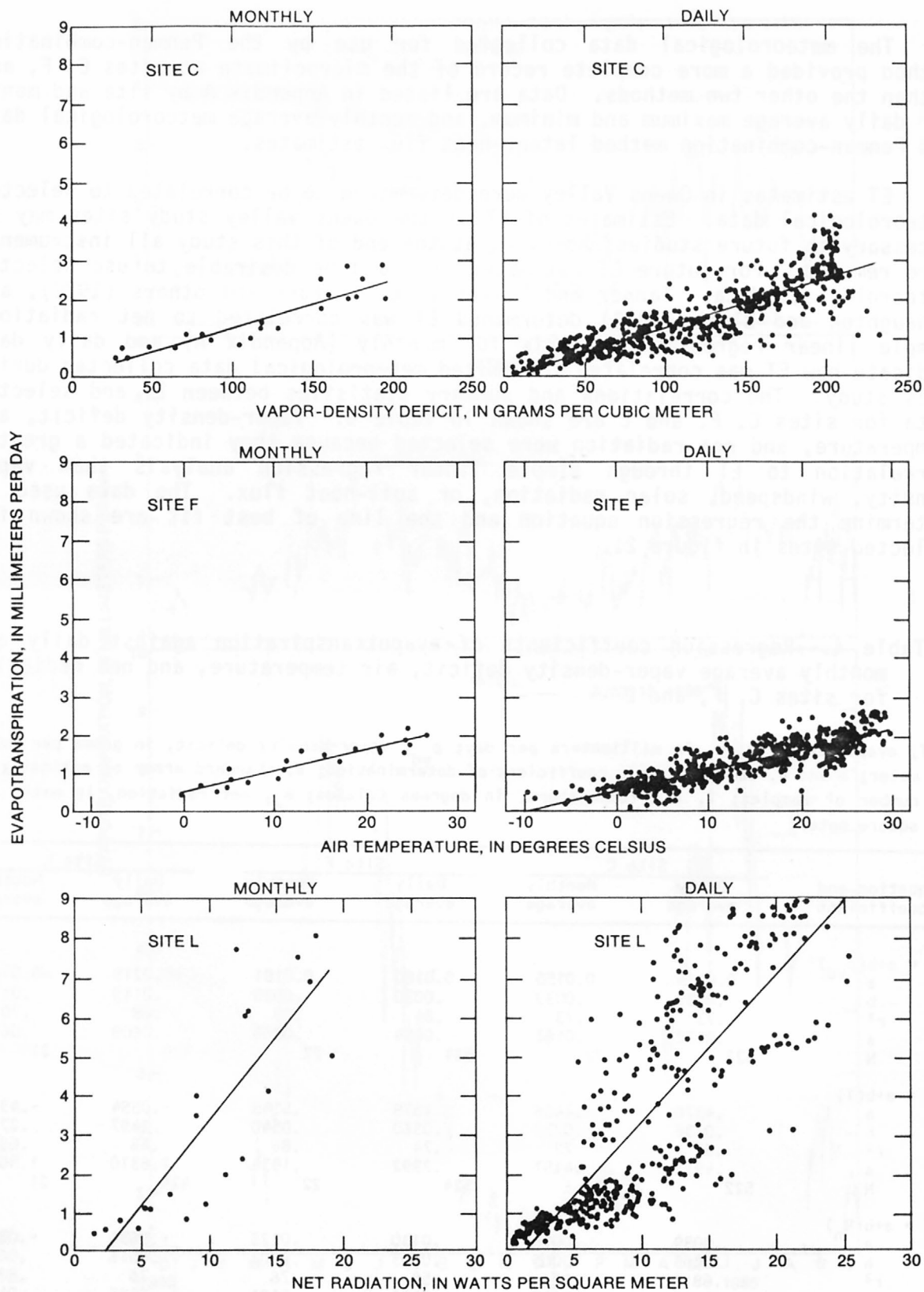
The meteorological data collected for use by the Penman-combination method provided a more complete record of the microclimate at sites C, F, and L than the other two methods. Data are listed in Appendix A by site and month for daily average maximum and minimum, and monthly average meteorological data and Penman-combination method latent-heat flux estimates.

ET estimates in Owens Valley were determined to be correlated to selected meteorological data. Estimates of ET at the Owens Valley study sites may be necessary in future studies; however, at the end of this study all instruments were removed. For future ET estimates it would be desirable to use selected meteorological data. Tanner and Pelton (1960), Storr and others (1970), and McNaughton and Black (1973) determined ET was correlated to net radiation. Simple linear regression analysis for monthly (Appendix A) and daily data indicate how ET was correlated to limited meteorological data collected during this study. The correlations and summary statistics between ET and selected data for sites C, F, and L are shown in table 4. Vapor-density deficit, air temperature, and net radiation were selected because they indicated a greater correlation to ET through simple linear regression analysis than vapor density, windspeed, solar radiation, or soil-heat flux. The data used to determine the regression equation and the line of best fit are shown for selected sites in figure 21.

Table 4.--Regression coefficients of evapotranspiration against daily and monthly average vapor-density deficit, air temperature, and net radiation for sites C, F, and L

[ET, evapotranspiration, in millimeters per day;  $\rho_{vd}$ , vapor-density deficit, in grams per cubic meter; a and b, constants;  $r^2$ , coefficient of determination; s, standard error of estimate; N, number of samples; T, air temperature, in degrees Celsius;  $R_n$ , net radiation, in watts per square meter]

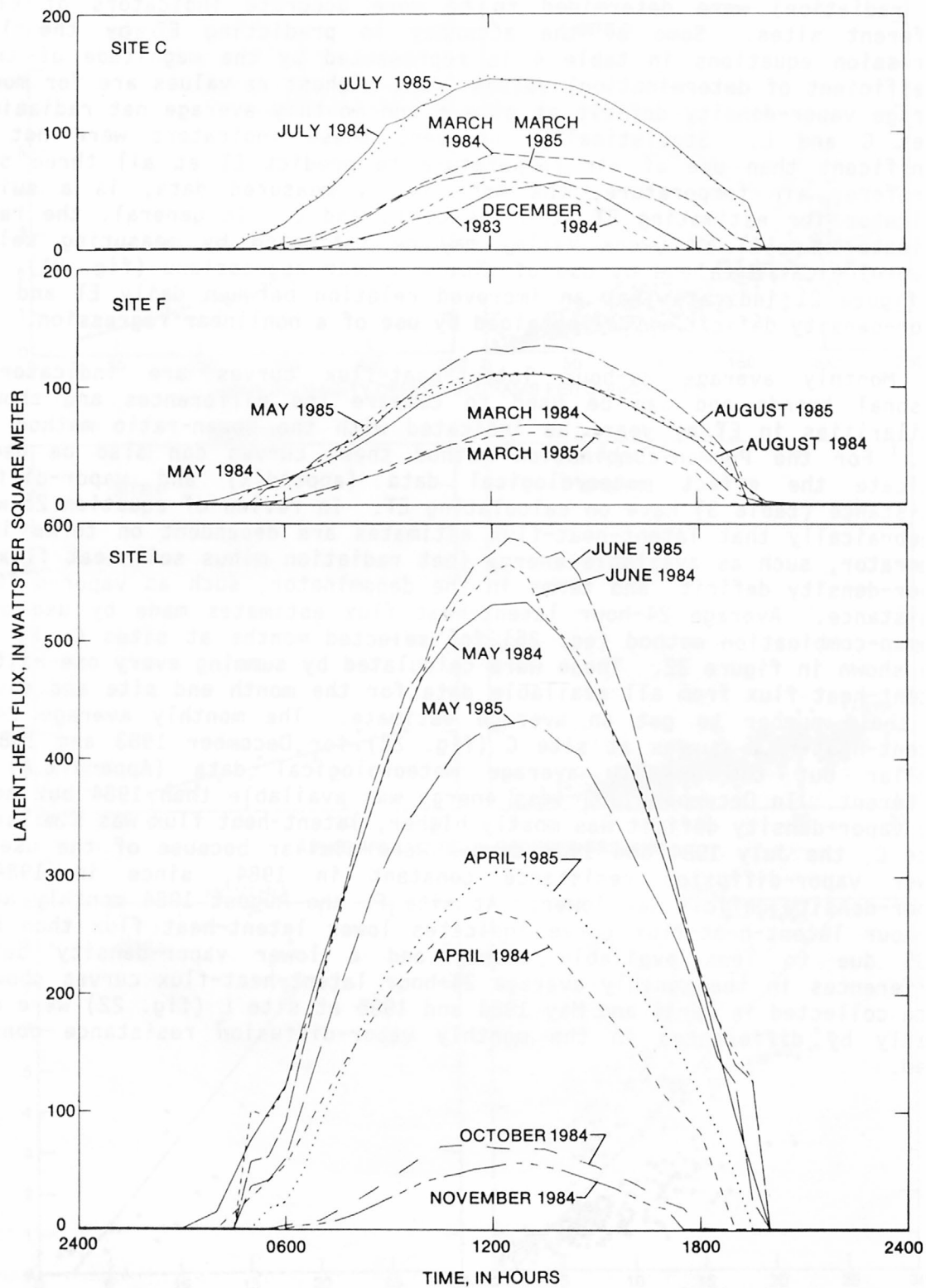
Equation and coefficient	Site C		Site F		Site L	
	Daily average	Monthly average	Daily average	Monthly average	Daily average	Monthly average
ET = a+b( $\rho_{vd}$ )						
a	0.0154	0.0155	0.0180	0.0191	-0.0219	-0.0402
b	.0039	.0039	.0030	.0029	.0149	.0171
$r^2$	.73	.73	.84	.89	.69	.70
s	.0172	.0161	.0094	.0068	.0609	.0614
N	522	22	524	22	424	21
ET = a+b(T)						
a	.4376	.4406	.4879	.5145	-.0554	-.4358
b	.0736	.0732	.0560	.0540	.2457	.2744
$r^2$	.67	.72	.74	.86	.66	.69
s	.4912	.4151	.2992	.1934	1.6310	1.5660
N	522	22	524	22	424	21
ET = a+b( $R_n$ )						
a	.0039	.0018	.0130	.0123	-.0634	-.0827
b	.0005	.0005	.0003	.0003	.0016	.0017
$r^2$	.68	.82	.58	.76	.76	.82
s	.0187	.0130	.0151	.0101	.0535	.0468
N	522	22	524	22	424	21



**Figure 21.** Linear regression of monthly and daily evapotranspiration estimated by the Penman-combination method for vapor-density deficit at site C, air temperature at site F, and net radiation at site L.

Different meteorological data (vapor-density deficit, air temperature, or net radiation) were determined to be more accurate indicators of ET for different sites. Some of the accuracy in predicting ET by the linear regression equations in table 4 is represented by the magnitude of the  $r^2$  (coefficient of determination) values. The highest  $r^2$  values are for monthly average vapor-density deficit at site F and monthly average net radiation at sites C and L. Statistically, however, these indicators were not more significant than use of air temperature to predict ET at all three sites. Therefore, air temperature, the most easily measured data, is a suitable indicator for estimating ET at sites C, F, and L. In general, the results indicate that ET in Owens Valley may be estimated by measuring selected meteorological data and by use of simple linear regressions (fig. 21). Data in figure 21 indicate that an improved relation between daily ET and daily vapor-density deficit may be obtained by use of a nonlinear regression.

Monthly average 24-hour latent-heat-flux curves are indicators of seasonal trends and can be used to compare the differences and show the similarities in ET by year, as indicated with the Bowen-ratio method (fig. 15). For the Penman-combination method these curves can also be used to indicate the effect meteorological data (appendix) and vapor-diffusion resistance (table 3) have on calculating ET. In review of equation 25 we see algebraically that latent-heat-flux estimates are dependent on terms in the numerator, such as available energy (net radiation minus soil-heat flux) and vapor-density deficit, and terms in the denominator, such as vapor-diffusion resistance. Average 24-hour latent-heat flux estimates made by use of the Penman-combination method (eq. 25) for selected months at sites C, F, and L are shown in figure 22. These were calculated by summing every one-half-hour latent-heat flux from all available data for the month and site and dividing by their number to get an average estimate. The monthly average 24-hour latent-heat-flux curves at site C (fig. 22) for December 1983 and 1984 are similar but the monthly average meteorological data (Appendix A) were different. In December 1983 less energy was available than 1984 but because the vapor-density deficit was mostly higher, latent-heat flux was similar. At site C, the July 1984 and 1985 curves were similar because of the use of a lower vapor-diffusion resistance constant in 1984, since in 1984 the vapor-density deficit was lower. At site F, the August 1984 monthly average 24-hour latent-heat-flux curve indicates lower latent-heat flux than August 1985 due to less available energy and a lower vapor-density deficit. Differences in the monthly average 24-hour latent-heat-flux curves shown for data collected in April and May 1984 and 1985 at site L (fig. 22) were caused mostly by differences in the monthly vapor-diffusion resistance constants used.



**Figure 22.** Comparison of average 24-hour latent-heat flux estimated by the Penman-combination method for selected months at sites C, F, and L.

## MONTHLY AND ANNUAL EVAPOTRANSPIRATION ESTIMATES

Monthly and annual estimates of ET are given in table 5. No single method used clearly provided the best ET estimate; therefore, the data in table 5 are the best estimated range of ET for 1984-85 in the plant communities studied. Daily ET estimates by site and method were averaged and multiplied by the number of days in the month to determine monthly ET estimates. Averages for the Bowen-ratio method are based on measurements made for as many as 14 days per month. Averages for the eddy-correlation method are based on measurements made for no more than 4 days per month by use of the direct and residual methods. Averages for the Penman-combination method commonly are derived from data for all days in a month. Estimates during the winter months for the Bowen-ratio and residual eddy-correlation methods were determined from the estimates by the Penman-combination method. During January 1984 at site L and February 1984 at sites C, F, and L, no data were collected for the Penman-combination method; the 1985 data were used instead. Data not available for the growing season were interpolated from the preceding and following months for that site. Annual ET estimates for the direct eddy-correlation method were not made because of the absence of available data owing to instrument malfunction.

The Bowen-ratio method estimates for sites F and L (table 5) indicate a decrease in annual ET from 1984 to 1985; however, estimates by the Penman-combination method indicate an increase. Instrument malfunctions for the Bowen-ratio method were more common in 1985, and as a result the instruments were not used as much in 1985 as in 1984. The Penman-combination method may more closely approximate the 1985 annual ET at sites C, F, and L. Estimates by the residual eddy-correlation method indicated a decrease in ET from 1984 to 1985 at sites A and J, and an increase at sites E and G. Estimates by the direct eddy-correlation method were lower in all cases than estimates by the residual eddy-correlation method. The residual eddy-correlation estimates indicated that annual ET at sites A, E, G, and J ranged within the high and low annual ET at sites F and L of the Bowen-ratio and Penman-combination estimates. These results were expected because the percentage of vegetation cover (table 2) at sites A, E, G, and J ranged within the percentage vegetation cover at sites F and L. Results indicate annual ET to be less for site C than for sites E and G; however, percentage vegetation cover at sites E and G was less than at site C. These results probably were caused by the different methods used rather than differences in vegetation cover.

The monthly and annual data (table 5) indicate that the Penman-combination method generally compares closely with the Bowen-ratio method. Daily ET estimates at the three sites where data were measured by these two methods also compare closely; however the Penman-combination method data were almost always higher than the Bowen-ratio data. Variation in results by these two methods may be explained by Bowen-ratio instrument error and therefore the estimates of the vapor-diffusion resistance constant. In some cases it appears the vapor-diffusion resistance constant was too small. The weather conditions for the periods of record when the respective methods were used could account for additional differences in the estimated ET. However, in review of the meteorological data, the Bowen-ratio method did not appear to represent data collected during atypical weather conditions.

Table 5.--Estimates of monthly and annual evapotranspiration for selected sites by use of the Bowen-ratio, eddy-correlation, and Penman-combination methods

Date	Estimated evapotranspiration, in millimeters									
	Bowen-ratio			Residual eddy-correlation; direct eddy-correlation in parenthesis				Penman-combination		
	site C	site F	site L	site A	site E	site G	site J	site C	site F	site L
1984										
January	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	24	19	<sup>2</sup> 24
February	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>2</sup> 31	<sup>2</sup> 31	<sup>2</sup> 30
March	<sup>3</sup> 36	<sup>3</sup> 29	<sup>3</sup> 56	<sup>3</sup> 53	<sup>3</sup> 60	<sup>3</sup> 32	<sup>3</sup> 48	31	27	45
April	40	27	82	75	90(14)	33(14)	66(17)	38	33	104
May	62	34	158	87(41)	85(21)	90(42)	118(65)	89	48	236
June	60	33	189	102(56)	72(13)	81(39)	129(53)	87	59	234
July	53	37	192	136	73(12)	101(55)	149(66)	65	53	192
August	56	34	115	158	50	65	126	79	47	128
September	27	21	69	123	45	57	81	43	48	71
October	19	12	<sup>1</sup> 25	<sup>1</sup> 32	<sup>1</sup> 32	<sup>1</sup> 32	<sup>1</sup> 32	30	41	25
November	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	<sup>1</sup> 22	23	26	17
December	<sup>1</sup> 14	<sup>1</sup> 14	<sup>1</sup> 14	<sup>1</sup> 14	<sup>1</sup> 14	<sup>1</sup> 14	<sup>1</sup> 14	15	14	14
Total	442	316	975	855	596	580	838	555	446	1,120
1985										
January	22	<sup>1</sup> 23	<sup>1</sup> 23	<sup>1</sup> 23	<sup>1</sup> 23	<sup>1</sup> 23	<sup>1</sup> 23	25	21	24
February	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	<sup>1</sup> 31	32	31	30
March	22	19	28	65	<sup>4</sup> 60	40(14)	40(7)	26	24	33
April	36	<sup>4</sup> 27	85	<sup>3</sup> 65	<sup>3</sup> 80	<sup>3</sup> 64	<sup>3</sup> 54	53	44	120
May	62	<sup>4</sup> 34	124	65	99	87	68	79	50	188
June	57	<sup>4</sup> 33	177	141(71)	78(27)	117(87)	168(82)	61	64	244
July	<sup>3</sup> 41	37	149	118(27)	53	87	143	63	61	216
August	25	31	102	93(58)	71(17)	90(66)	118(58)	64	57	156
September	<sup>4</sup> 27	<sup>4</sup> 21	<sup>4</sup> 69	<sup>4</sup> 123	<sup>4</sup> 45	<sup>4</sup> 57	<sup>4</sup> 81	35	39	58
October	<sup>4</sup> 19	9	17	<sup>1</sup> 40	<sup>1</sup> 40	<sup>1</sup> 40	<sup>1</sup> 40	35	49	37
Total	378	301	841	800	616	672	802	511	480	1,137

<sup>1</sup>Data estimated from Penman-combination method data.<sup>2</sup>185 data.<sup>3</sup>Data interpolated from preceding and following months.<sup>4</sup>1984 data.<sup>5</sup> Estimated annual total included November and December 1984 data.

Estimates of water use through ET in the Owens Valley by use of the annual data (table 5) were not made for the entire study area. Weeks and others (1985) indicated that extrapolating ET measurements in time and transferring them in space to nearby areas require that assumptions of uncertain reliability be made. Results of recent vegetation mapping of the valley indicate that the study sites occupy approximately 20 percent of the study area. In addition, the remainder of the valley may have a lower ET rate than some of the study area sites (Los Angeles Department of Water and Power; written commun., 1987). Therefore, extrapolating the annual ET estimates to the entire study area may provide an erroneously high estimate of water use through ET for the valley.

A summary of vegetation site characteristics and ET estimates is presented in table 6. These data are most useful for understanding the process of ET and developing and calibrating models of ET for the Owens Valley. These techniques are presented by M.R. Welch (U.S. Geological Survey, written commun., 1987). In addition, the ET estimates may be used in similar semiarid areas and vegetation communities where no other data are available. The sites were classified into plant communities on the basis of the dominant cover type (Los Angeles Department of Water and Power, written commun., 1987). The most common plant types listed were those that composed more than 50 percent of the total vegetation found at the sites. The annual ET estimates for 1984-85 for sites C, F, and L were determined by use of the Bowen-ratio and Penman-combination methods. The annual ET estimates for 1984-85 for sites A, E, G, and J were determined by use of the residual eddy-correlation method.

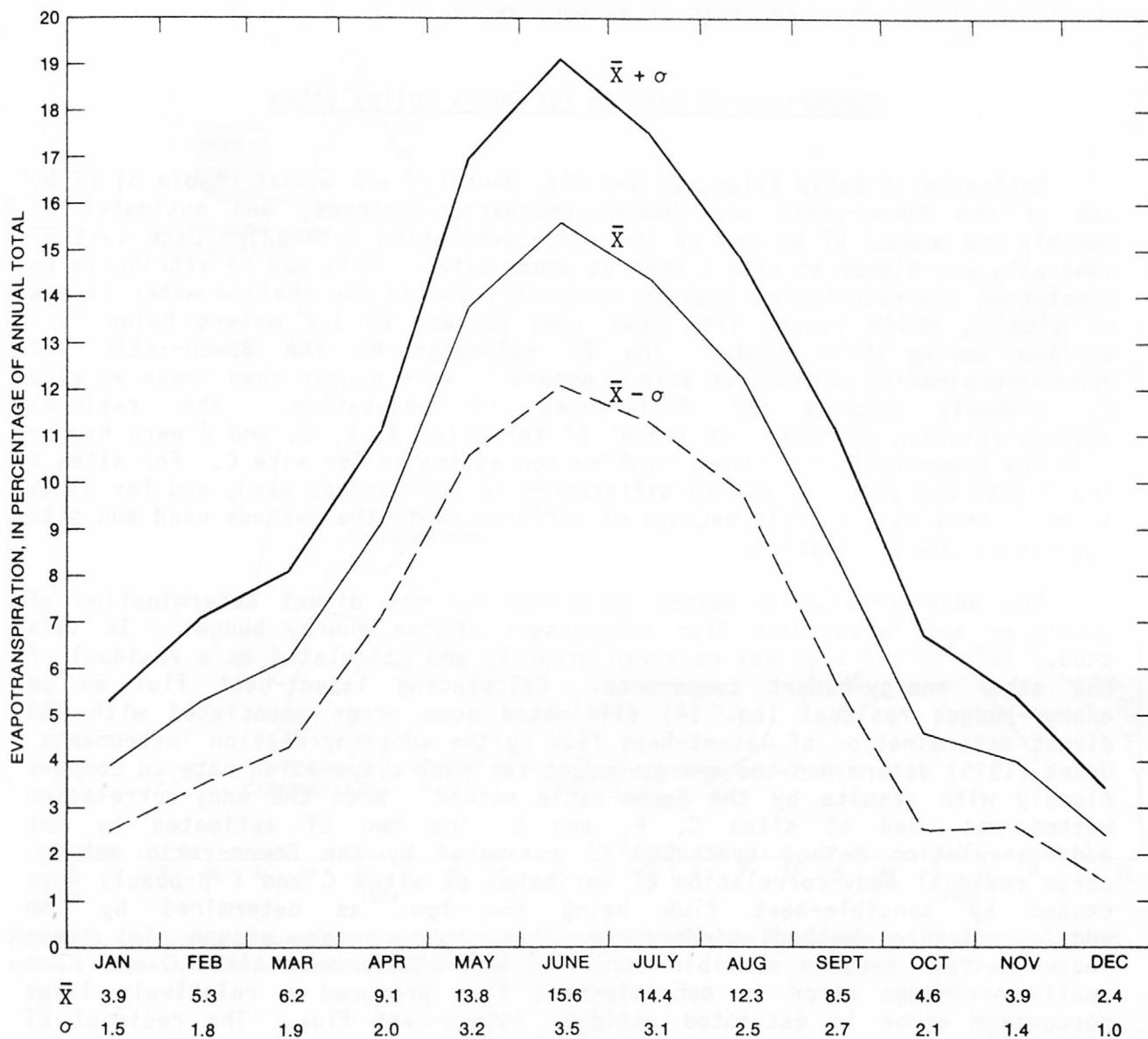
Monthly ET, expressed as a percentage of the average annual ET, is shown in figure 23. These monthly percentages, along with annual ET, may be used throughout Owens Valley to estimate the amount of monthly ET from the alkaline scrub and meadow plant communities. The monthly percentages were determined from the monthly and annual ET estimates (table 5) at sites C, F, and L by use of both the Bowen-ratio and Penman-combination methods and at sites A, E, G, and J by use of the residual eddy-correlation method.

The data shown in figure 23 are not substantially different if only specific methods, sites, or years are used. However, at site E, the maximum monthly ET occurred one month earlier than at other sites. At site E, plants may have been more dependent on soil water and less dependent on ground water throughout the growing season. At site L, a typical meadow community, the maximum percentage of ET was higher during May, June, and July than at other sites. This was probably because of the type and characteristics of the vegetation found at the site. The monthly percentages of annual ET at site L were  $17.2 \pm 2.6$  in May,  $20.5 \pm 1$  in June, and  $18.2 \pm 1$  in July. Although these data (fig. 23) were for a brief period of record (1984-85), the general distribution of ET during the year is highly dependent on net radiation and will be similar for other years and for most plant communities.

Table 6.--Vegetation characteristics, water-level and precipitation data, and the range in evapotranspiration estimates at the study sites

[Vegetation data from Los Angeles Department of Water and Power (written commun., 1984 and 1987). Evapotranspiration estimates are for all the annual data shown in table 5. --, no data]

Site	Plant community	Most common plant type		Total vegetation cover (percent)	Range of water levels for 1984 (meters below land surface)	Annual precipitation for 1984 (milli-meters)	Annual evapotranspiration estimates for 1984-85 (millimeters)		
		Common name	Composition of total vegetation (percent)				Maximum	Minimum	Mean
A	Alkali meadow	Alkali sacaton Russian thistle	43 22	42	3.2-4.7	--	855	800	828
C	Rabbitbrush meadow	Salt grass Rubber rabbitbrush	34 25	35	3.1-3.5	150	555	378	471
E	Desert sink scrub	Rubber rabbitbrush Alkali sacaton Mormon Tea	24 23 8	26	3.1-3.3	--	616	596	606
F	Desert sink scrub	Salt grass Greasewood	34 27	24	2.4-2.7	160	480	301	385
G	Alkali meadow	Salt grass Alkali sacaton Rubber rabbitbrush	30 13 9	33	2.2-2.7	--	672	580	626
J	Alkali meadow	Nevada saltbrush Alkali sacaton Rubber rabbitbrush	29 21 16	50	1.4-2.2	--	838	802	820
L	Rush and sedge meadow	Salt grass Alkali sacaton Baltic rush	20 17	72	0.0-1.2	80	1,137	841	989



**Figure 23.** Monthly percentage ( $\bar{X}$ , algebraic mean;  $\sigma$ , standard deviation) of average annual evapotranspiration for 1984-85.

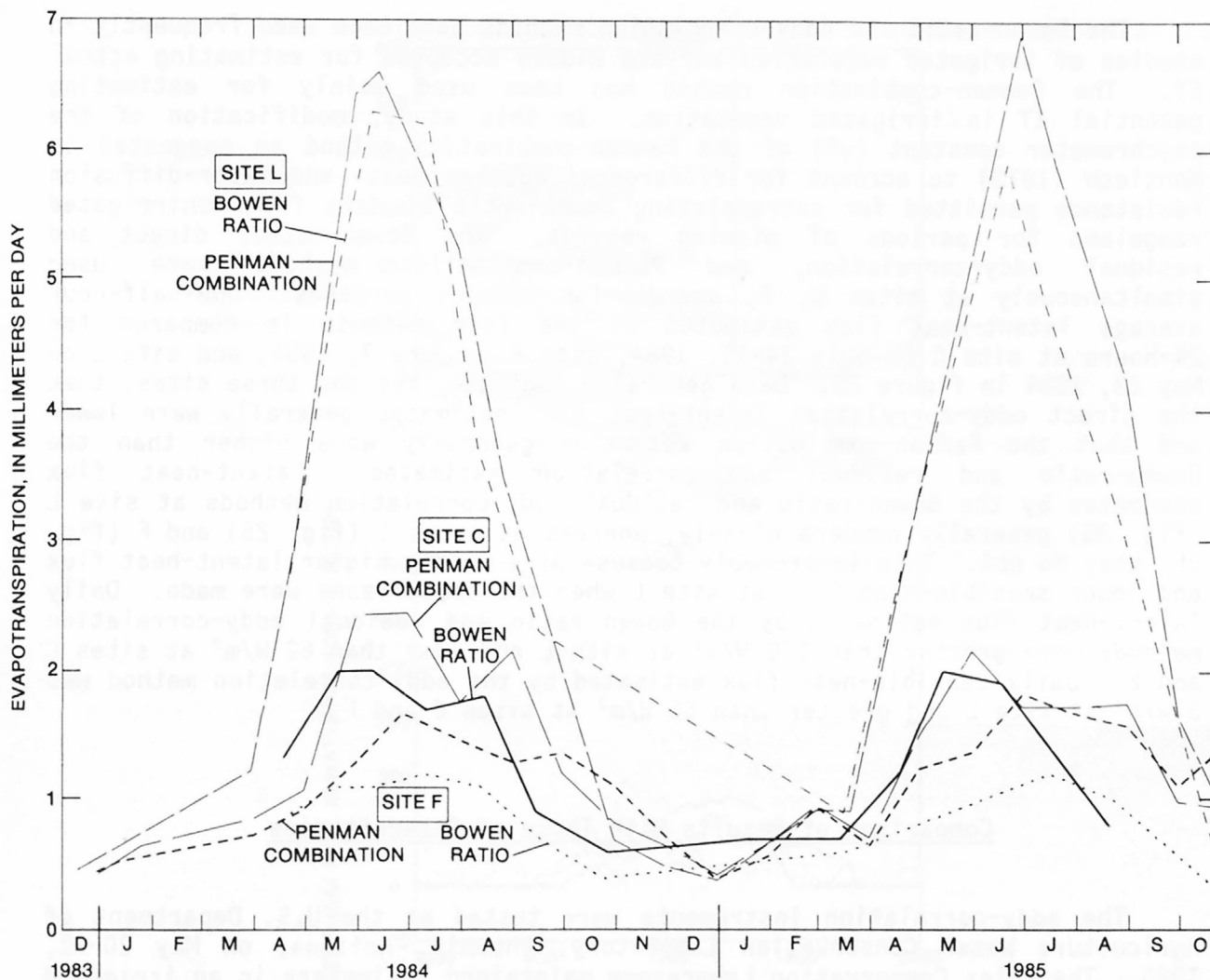
## ANALYSIS OF METHODS AND RESULTS

### Comparison of Results for Owens Valley Sites

Estimates of daily (figs. 13 and 20), monthly, and annual (table 5) ET by use of the Bowen-ratio and Penman-combination methods, and estimates of monthly and annual ET by use of the eddy-correlation method indicate that ET generally was higher at site L than at other sites. This may be attributed to vegetation characteristics (meadow community) and to the shallow water levels at site L, which ranged from near land surface to 1.2 meters below land surface during this study. The ET estimates by the Bowen-ratio and Penman-combination methods at site C generally were higher than those at site F, probably because of differences in vegetation. The residual eddy-correlation estimates of annual ET for sites A, E, G, and J were higher than the Bowen-ratio and Penman-combination estimates for site C. For sites E and G this was probably due to differences in the methods used, and for sites A and J, this was probably because of differences in the methods used and site vegetation characteristics.

The eddy-correlation method permitted for the direct determination of sensible- and latent-heat flux independent of the energy budget. In this study, latent-heat flux was measured directly and calculated as a residual of the other energy-budget components. Calculating latent-heat flux as an energy-budget residual (eq. 14) eliminated some error associated with the direct determination of latent-heat flux by the eddy-correlation instruments. Grant (1975) determined the energy-budget residual evaporation rate to compare closely with results by the Bowen-ratio method. When the eddy-correlation method was used at sites C, F, and L, the two ET estimates by the eddy-correlation method bracketed ET estimated by the Bowen-ratio method. Large residual eddy-correlation ET estimates at sites C and F probably were caused by sensible-heat flux being too low, as determined by the eddy-correlation method, indicating that some error occurs in these measurements. Because sensible-heat flux was dominant at sites C and F, a small percentage error in sensible-heat flux produced a relatively large percentage error in estimated residual latent-heat flux. The residual ET estimates indicated an upper limit to the flux values. Direct ET estimates were lower than other estimates and indicated a lower limit to the flux values. Weeks and others (1987), using the same type of instruments, determined similar results. ET estimates at site L by use of Bowen-ratio and residual eddy-correlation methods compare closely because sensible-heat flux was small.

The Penman-combination method had the advantage of a longer period of record; however, it was not useful unless first calibrated by the Bowen-ratio method. Once calibrated it provided the potential for accurate daily, monthly, and yearly ET estimates for sites C, F, and L. Monthly average ET, in millimeters per day, estimated at sites C, F, and L for the Bowen-ratio and Penman-combination methods is compared in figure 24. The results indicate that the ET estimates by the Penman-combination method generally were higher; differences may be attributed to calibration errors. The vapor-diffusion resistance constant may have been too small so that when using the Penman-combination method, ET was overestimated.



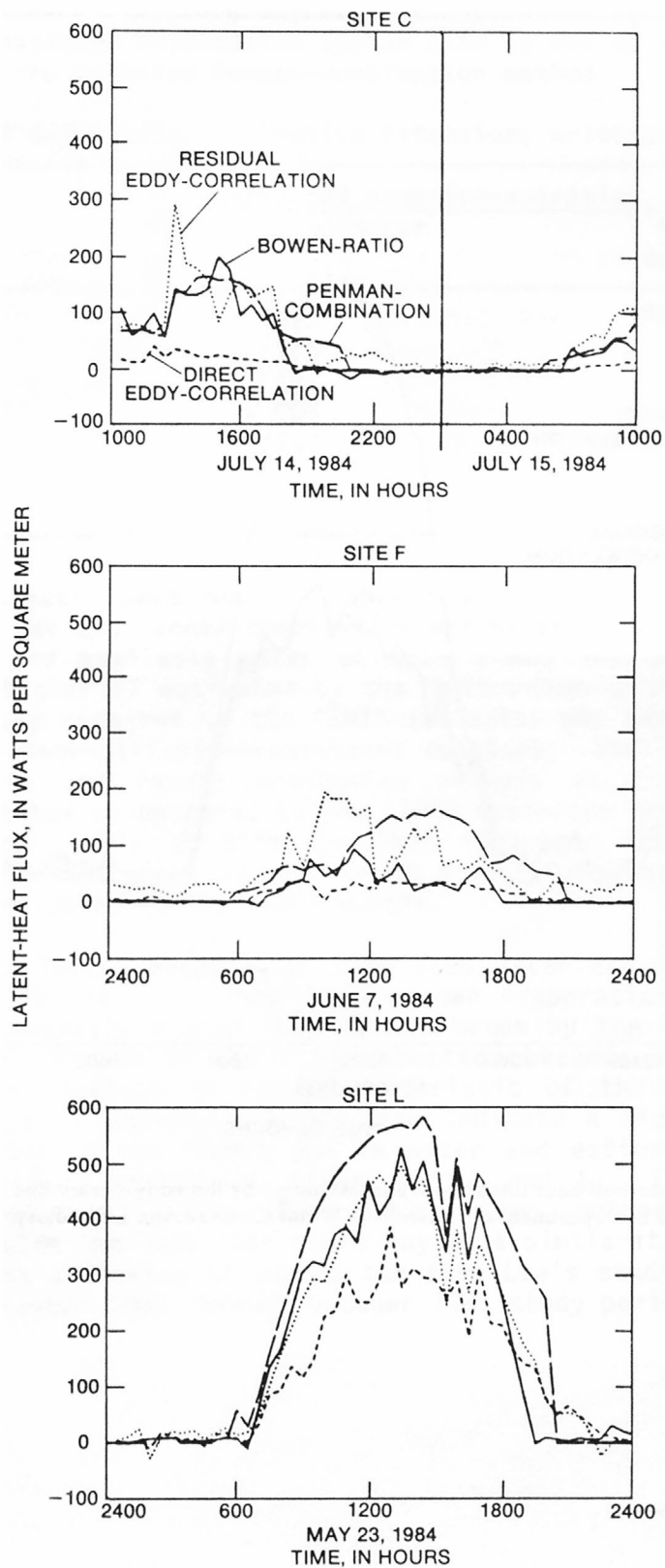
**Figure 24.** Comparison of monthly average evapotranspiration estimated by the Bowen-ratio and Penman-combination methods at sites C, F, and L, December 1983-October 1985.

The Bowen-ratio and eddy-correlation methods have been used frequently in studies of irrigated vegetation and are widely accepted for estimating actual ET. The Penman-combination method has been used mainly for estimating potential ET in irrigated vegetation. In this study, modification of the psychrometer constant ( $\gamma^*$ ) of the Penman-combination method as suggested in Montieth (1973) to account for differences between heat- and vapor-diffusion resistance permitted for extrapolating Bowen-ratio ET data from nonirrigated rangeland for periods of missing records. The Bowen-ratio, direct and residual eddy-correlation, and Penman-combination methods were used simultaneously at sites C, F, and L, for testing purposes. One-half-hour average latent-heat flux estimated by the four methods is compared for 24-hours at site C on July 14-15, 1984, site F on June 7, 1984, and site L on May 23, 1984 in figure 25. Data generally indicate, for the three sites, that the direct eddy-correlation latent-heat flux estimates generally were lower and that the Penman-combination estimates generally were higher than the Bowen-ratio and residual eddy-correlation estimates. Latent-heat flux estimates by the Bowen-ratio and residual eddy-correlation methods at site L (fig. 25) generally compare closely, whereas at sites C (fig. 25) and F (fig. 25) they do not. This is probably because of a mostly higher latent-heat flux and lower sensible-heat flux at site L when the comparisons were made. Daily latent-heat flux estimates by the Bowen ratio and residual eddy-correlation methods were greater than  $170 \text{ W/m}^2$  at site L and less than  $62 \text{ W/m}^2$  at sites C and F. Daily sensible-heat flux estimated by the eddy-correlation method was  $3 \text{ W/m}^2$  at site L and greater than  $65 \text{ W/m}^2$  at sites C and F.

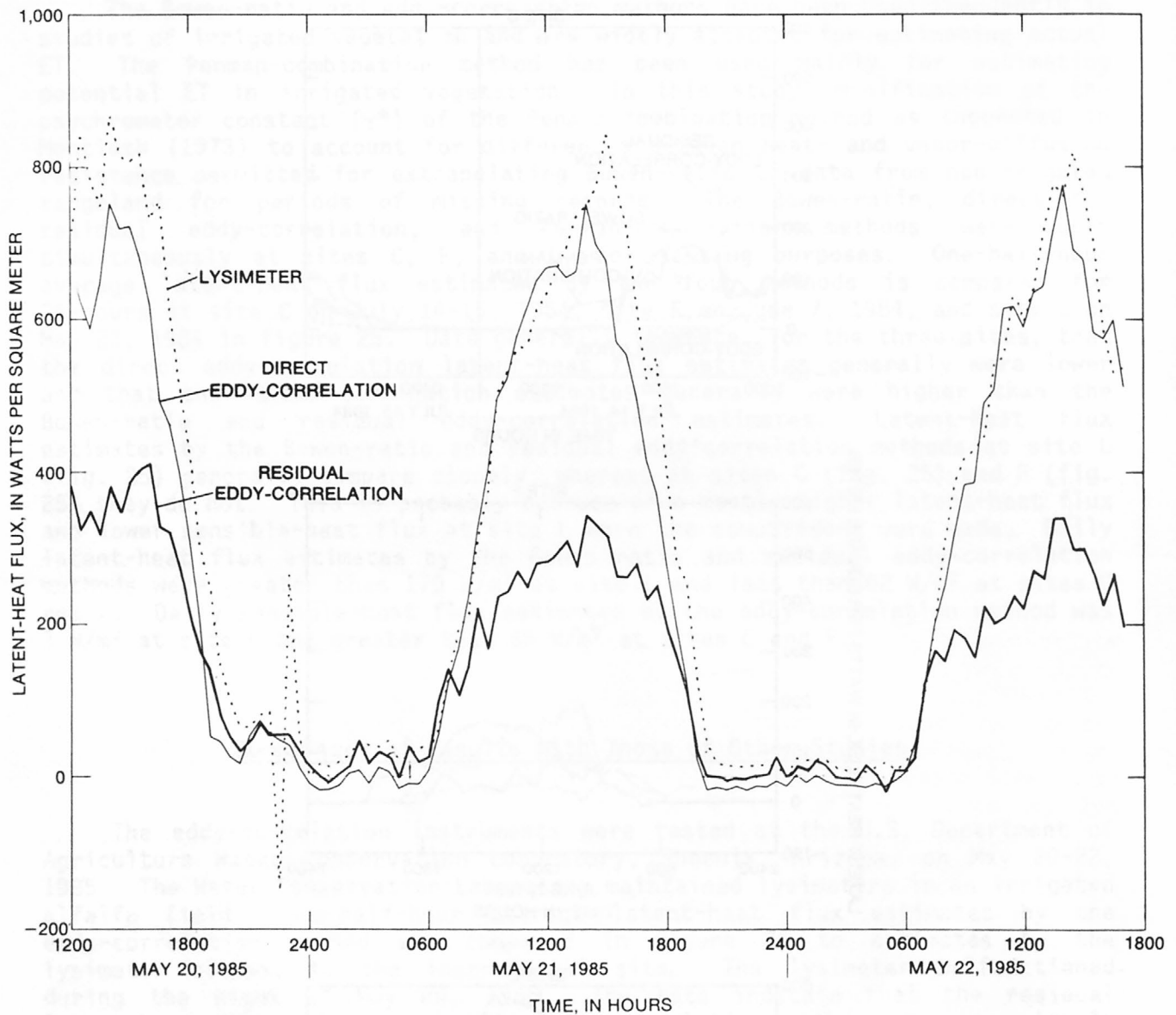
#### Comparison of Results With Those of Other Studies

The eddy-correlation instruments were tested at the U.S. Department of Agriculture Water Conservation Laboratory, Phoenix, Arizona, on May 20-22, 1985. The Water Conservation Laboratory maintained lysimeters in an irrigated alfalfa field. One-half-hour average latent-heat flux estimates by the eddy-correlation method are compared in figure 26 to estimates by the lysimeter closest to the instruments' site. The lysimeter malfunctioned during the night of May 20, 1985. The data indicate that the residual latent-heat flux estimated by the eddy-correlation method compares closely with the lysimeter data and that the direct latent-heat flux estimates were consistently low. During this test, daily estimates of sensible-heat flux ranged from  $-69$  to  $-45 \text{ W/m}^2$ ; daily estimates of latent-heat flux by the residual eddy-correlation method ranged from  $243$  to  $260 \text{ W/m}^2$ .

The California Irrigation Management Information System (CIMIS) ET study was concurrent with this study in Owens Valley. The CIMIS study was done on an irrigated alfalfa crop of uniform height at the Sunland cooperative weather station near Bishop, California (fig. 1). Monthly ET estimates in 1985 were made at this site by use of a floating lysimeter and the modified Penman-combination method (Doorenbos and Pruitt, 1977) using on-site meteorological instrumentation. Available estimates are shown in table 7.



**Figure 25.** Comparison of one-half-hour latent-heat flux estimated by the Bowen-ratio, direct and residual eddy-correlation, and Penman-combination methods at site C, July 14-15, 1984; site F, June 7, 1984; and site L, May 23, 1984.



**Figure 26.** Comparison of one-half-hour latent-heat flux estimated by the eddy-correlation method and a lysimeter at Phoenix, Arizona, May 20-22, 1985 (U.S. Department of Agriculture Water Conservation Laboratory, written commun., 1985, and this study).

Table 7.--Estimates of 1985 monthly evapotranspiration for the California Irrigation Management Information System site by use of a floating lysimeter and the modified Penman-combination method

[University of California Cooperative Extension, written commun., 1985]

Month	Estimated evapotranspiration, in millimeters	
	Floating lysimeter	Modified Penman-combination method
May	162	211
June	176	209
July	192	199
August	208	182
September	103	149
October	67	108

These ET estimates were mostly higher than the estimates in this study (table 5), except for the Penman-combination estimates at site L. The percent vegetation cover and available water at site L was similar to that of the CIMIS site. The higher ET estimates by the Penman-combination method at site L for June and July compared to the CIMIS estimates may have been because of the use of a low vapor-diffusion-resistance constant. The lower ET estimates by the Bowen-ratio and Penman-combination methods at site L for August, September, and October as compared to the CIMIS estimates probably were caused by the lower water table at site L. This indicates that there was less available water for the native vegetation at site L, whereas the alfalfa crop continued to be irrigated during those months.

Lee (1912) collected evaporation data from water and land surfaces near Independence, California. His results from pan evaporation indicate monthly estimates to be generally higher than ET estimates by the Penman-combination method at sites C, F, and L. This is expected, because evaporation from a free-standing water surface is not characteristic of the study-area sites. Regression analysis of monthly average data indicate a high correlation for Lee's estimated evaporation from a pan in water and estimated monthly ET by the Penman-combination method at sites C, F, and L. The data does not indicate a correlation exists for Lee's other methods of estimating evaporation. Results indicate that there may be a similarity for the seasonal climatic conditions affecting ET during the time Lee's studies were conducted and during the December 1983 through October 1985 study period.

## Limitations of Methods

The three methods used in this study to estimate ET in Owens Valley are mathematical models that have common and method-dependent error limitations. The limitations for all three methods that may have occurred include the following:

1. ET estimates by use of energy-budget methods did not account for photosynthesis, respiration, and heat storage in the crop canopy.
2. Instrument measurement errors of net radiation was possible because the shortwave calibration of these instruments was assumed to be the same for the longwave component.
3. Instrument measurement errors of soil-heat flux were possible because of the storage of energy in the soil above the soil-heat-flux plate and the effect of temperature on the calibration constant of each plate, was considered negligible over a 24-hour period.
4. The measurements used for estimating ET were collected for one dimension, whereas ET occurs in three dimensions.
5. Daily estimates were made for a limited number of days during the month and these incomplete data were averaged to determine monthly values; incomplete months were estimated to determine annual values.
6. The Owens Valley plant communities studied were native rangeland alkaline scrub and meadow vegetation, whereas the three ET methods used for this study were developed and tested on irrigated crops.

The Bowen-ratio method in Owens Valley was determined to produce erroneous results during times when temperature inversion occurred, such as at sunset, sunrise, and occasionally at nighttime. The psychrometers used for this method were satisfactory in most cases; however, their accuracy at times raised questions as to the validity of the results. Mechanically the instruments did not always function properly. Periods of high winds or precipitation could cause the psychrometers to fall below the switching mechanism and shut the system off. The drip-fed water reservoir, necessary for wet-bulb depression, could malfunction and cause the wicks of the wet-bulb psychrometers to dry up. The Bowen-ratio method required more time to reduce data and review the results than the eddy-correlation or Penman-combination methods. In general, the Bowen-ratio method did provide results that were used to estimate daily, monthly, and annual ET at the selected sites in Owens Valley.

Latent-heat flux determined directly for the eddy-correlation method by the Lyman-alpha hygrometer produced questionable results. This was evident from closure of the energy budget (eq. 13) which typically was measured during this study at 40 to 60 percent. Residual ET estimates at sites C and F generally were higher than the ET estimates by the Bowen-ratio method. At these sites sensible-heat flux was a major component of the energy budget, indicating that the sensible-heat flux estimates did have some error. The residual ET estimates probably were more accurate under conditions of low sensible-heat flux, such as at site L and in irrigated alfalfa fields (as evident from the data collected in Phoenix, Arizona) (fig. 26). The errors with this method were minor and the instruments were easily moved; however, because of the delicate construction of the instruments they were not left unattended for longer than 24-hours. This method required a computing data logger, but data reduction was simple and easily reviewed. The limited amount of data collected by this method was a disadvantage, because monthly estimates were based on periods of only up to 4 days. The estimates of annual ET at sites A, E, G, and J do compare closely with those of other methods at sites C, F, and L, indicating that even limited data by this method are useful.

The Penman-combination method required the least field effort. Few instrument malfunctions occurred and maintenance was minimal. Data reduction and storage were simple. Potential ET estimates made by this method were indicated to be erroneous because of the climatic conditions of the valley; as a result this method generally is not recommended unless calibrated with actual ET estimates, such as those from the Bowen-ratio or eddy-correlation methods. For this study, with actual ET estimates determined by the Bowen-ratio method, the Penman-combination method was calibrated to provide estimates of actual ET. Calibration errors were indicated from the range and standard deviation of the monthly vapor-diffusion resistance constants (table 3) and the lack of exact agreement between Penman-combination data and the Bowen-ratio data. The vapor-diffusion resistance constant necessary for the Penman-combination method is difficult to determine and may be impossible to estimate if the method is used alone. The Owens Valley sites included rangeland vegetation that range from low-density greasewood to high-density meadow. The range of vapor-diffusion resistance constants may be used in other semiarid and arid vegetation communities where actual ET estimates are not available. However, these constants need to be adjusted to a seasonal trend rather than the exact values used in this study.

## SUMMARY

In Owens Valley, ET accounts for the loss of a substantial quantity of ground water. The other major source of outflow in the water budget of the valley is the surface and ground water that is exported to the city of Los Angeles. To improve the definition of the water budget in Owens Valley, estimates of ET were made at seven representative locations on the valley floor. ET measurements were made at three sites by use of the Bowen-ratio or Penman-combination methods; measurements at the other four sites were made by the direct and residual eddy-correlation methods. These estimates provided an indication of ET for selected alkaline scrub and meadow plant communities in Owens Valley. Estimates of ET for 1984-85 in the study area ranged from 300 mm per year at a low-density scrub site to 1,100 mm per year at a high-density meadow site. The monthly percentage of annual ET was determined to be similar for all study sites.

Estimates of ET by the Bowen-ratio, eddy-correlation, and Penman-combination methods were in close agreement. The results appear satisfactory when compared to other estimates of ET and indicate that these methods were suitable for use in the Owens Valley studies. The Bowen-ratio data were occasionally adjusted to account for temperature inversion. ET estimates by the direct eddy-correlation method generally were smaller than those of the Bowen-ratio method and may indicate a lower limit for ET. ET estimates by the residual eddy-correlation method generally were larger than those of the Bowen-ratio method and may indicate an upper limit for ET. The psychrometer constant of the Penman-combination method was modified to account for differences in heat- and vapor-diffusion resistance between areas measured in various parts of the rangeland of Owens Valley. If the method is not modified, it may not be accurate in calculating potential ET in the native vegetation communities of the valley. However, monthly vapor-diffusion resistance constants that were estimated for sites by use of the Bowen-ratio method were used by the Penman-combination method to provide improved estimates of actual ET. Differences in the ET estimates by these two methods probably were caused by calibration errors, whereby the vapor-diffusion resistance constant was underestimated. One-half-hour vapor-diffusion resistance estimates did not indicate a diurnal trend and the correlation with meteorological data measured for this study was insignificant. Monthly vapor-diffusion resistance constants generally indicated a seasonal trend in these data.

The biophysical equations used to estimate ET in this report were based mainly on established principles. The description of instrumentation will aid other researchers who use battery-operated data loggers. The meteorological data compiled and measured as part of this study represents an extensive data base of nearly 2 year's duration that is representative of a semiarid to arid environment. Simple linear regression relations were developed for estimating ET by using vapor-density deficit, air temperature, and net radiation data. The methods used by this study may be transferable to semiarid and arid rangeland areas in the Western United States.

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APPENDIX A

## APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L

[°C, degree Celsius; g/m<sup>3</sup>, grams per cubic meter; m/s, meters per second; W/m<sup>2</sup>, watts per square meter]

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE C								
<u>December 1983</u>								
Maximum.....	5.2	3.5	5.0	3.2	132	58	11	24
Minimum.....	1.6	1.1	2.3	1.2	62	4	-4	8
Mean.....	3.5	2.2	4.3	2.0	105	27	3	15
<u>January 1984</u>								
Maximum.....	9.9	6.2	5.1	5.3	157	45	29	31
Minimum.....	-2.7	2.5	1.9	1.6	112	10	5	15
Mean.....	5.3	4.1	3.6	2.5	133	31	16	22
<u>March 1984</u>								
Maximum.....	14.6	10.0	4.8	6.0	294	138	24	42
Minimum.....	4.6	4.0	1.9	2.2	150	4	-5	15
Mean.....	9.7	7.2	2.8	3.6	242	111	13	29
<u>April 1984</u>								
Maximum.....	17.8	14.3	4.0	6.0	344	166	37	56
Minimum.....	4.2	4.5	1.7	2.0	209	39	4	15
Mean.....	12.1	9.4	2.6	3.6	290	129	20	36
<u>May 1984</u>								
Maximum.....	25.5	23.6	4.1	4.5	389	208	45	116
Minimum.....	15.1	10.5	2.2	2.2	232	99	14	43
Mean.....	21.7	17.8	3.2	3.0	348	172	34	81
<u>June 1984</u>								
Maximum.....	28.3	26.2	6.2	4.9	392	207	36	115
Minimum.....	17.6	11.9	2.8	2.2	322	148	19	55
Mean.....	22.0	16.8	4.2	3.1	358	194	30	82
<u>July 1984</u>								
Maximum.....	32	31.9	13.2	3.8	381	224	63	92
Minimum.....	19.5	6.9	3.2	2.1	161	88	5	24
Mean.....	26.3	19.7	7.0	2.8	310	178	31	59

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE C--Continued								
<u>August 1984</u>								
Maximum.....	26.8	22.3	14.5	4.5	361	214	59	97
Minimum.....	20.6	3.5	3.4	1.9	125	75	-5	25
Mean.....	24.3	16.0	7.7	2.9	283	156	33	72
<u>September 1984</u>								
Maximum.....	26.1	22.0	9.6	4.0	294	166	33	61
Minimum.....	12.6	10.0	2.2	2.0	165	76	10	26
Mean.....	21.6	15.6	5.2	2.7	246	119	21	40
<u>October 1984</u>								
Maximum.....	17.6	12.8	6.3	5.7	231	143	31	41
Minimum.....	3.1	3.1	1.7	1.8	102	40	-4	11
Mean.....	11.9	8.5	3.2	2.9	187	87	9	28
<u>November 1984</u>								
Maximum.....	11.9	9.2	5.4	4.6	175	82	16	41
Minimum.....	-0.2	1.1	1.7	1.3	52	20	-23	4
Mean.....	5.3	4.5	3.2	2.3	142	64	2	22
<u>December 1984</u>								
Maximum.....	6.8	3.2	6.3	7.0	135	67	0	26
Minimum.....	-10.7	.3	1.8	1.1	26	5	-23	4
Mean.....	-0.9	1.4	3.6	2.1	102	35	-14	14
<u>January 1985</u>								
Maximum.....	8.1	6.5	4.9	5.9	161	82	27	37
Minimum.....	-1.3	.3	1.4	1.3	29	14	-20	3
Mean.....	2.6	3.3	3.0	2.5	127	48	1	23
<u>February 1985</u>								
Maximum.....	11.3	8.6	3.8	7.3	216	91	30	46
Minimum.....	-2.5	1.0	1.4	1.2	99	37	-2	10
Mean.....	5.2	5.4	2.3	2.7	174	71	17	32
<u>March 1985</u>								
Maximum.....	13.4	9.5	4.1	6.4	275	142	37	37
Minimum.....	1.5	3.1	1.2	2.3	111	51	0	13
Mean.....	6.7	6.0	2.4	3.7	217	104	19	24

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE C--Continued								
<u>April 1985</u>								
Maximum.....	19.7	15.4	4.0	7.4	328	176	40	67
Minimum.....	7.9	6.7	1.7	2.1	166	67	8	21
Mean.....	15.7	11.9	3.1	3.0	294	156	29	50
<u>May 1985</u>								
Maximum.....	22.5	17.6	4.2	5.6	360	208	36	92
Minimum.....	14.4	10.1	2.3	2.2	211	101	13	51
Mean.....	19.0	14.5	3.2	3.5	327	182	24	72
<u>June 1985</u>								
Maximum.....	28.7	26.6	7.5	3.3	370	232	66	72
Minimum.....	12.1	6.3	2.8	2.2	136	78	-2	18
Mean.....	24.6	20.8	4.4	2.6	337	196	37	58
<u>July 1985</u>								
Maximum.....	29.9	30.3	12.3	4.0	368	208	53	81
Minimum.....	22.0	7.6	2.9	1.9	199	100	6	38
Mean.....	26.5	21.4	5.7	2.8	307	173	28	58
<u>August 1985</u>								
Maximum.....	26.9	24.6	5.7	3.3	342	185	32	66
Minimum.....	21.1	16.7	2.9	1.9	251	114	22	50
Mean.....	25.2	21.8	3.9	2.6	316	161	27	58
<u>September 1985</u>								
Maximum.....	24.8	20.1	8.3	4.1	300	161	40	56
Minimum.....	12.0	3.9	2.7	1.9	113	45	-4	16
Mean.....	17.4	12.0	4.2	2.7	243	118	19	33
<u>October 1985</u>								
Maximum.....	20.8	16.8	4.4	4.6	237	105	20	48
Minimum.....	6.6	4.1	1.8	1.7	86	22	-14	10
Mean.....	13.6	10.3	2.9	2.8	193	81	9	32

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE F								
December 1983								
Maximum.....	8.4	4.0	6.6	3.9	113	51	12	22
Minimum.....	0.1	.7	2.5	1.1	67	13	-3	9
Mean.....	3.9	2.3	4.4	2.0	110	27	4	15
January 1984								
Maximum.....	9.5	5.7	5.2	4.8	142	35	24	23
Minimum.....	-0.8	1.6	2.8	1.4	112	19	0	9
Mean.....	5.0	3.7	3.8	2.8	128	26	16	18
March 1984								
Maximum.....	14.7	10.5	4.5	6.5	295	125	47	36
Minimum.....	5.5	3.7	1.9	2.0	195	63	0	14
Mean.....	10.6	7.7	2.8	3.7	246	96	28	24
April 1984								
Maximum.....	16.7	12.7	3.9	5.2	350	182	33	51
Minimum.....	4.5	4.4	1.7	2.3	148	85	5	17
Mean.....	11.2	8.4	2.7	3.8	292	139	18	31
May 1984								
Maximum.....	26.1	23.6	5.1	3.9	382	200	43	57
Minimum.....	15.4	10.5	2.5	2.4	237	115	15	26
Mean.....	21.9	17.4	3.8	3.1	351	166	28	43
June 1984								
Maximum.....	27.2	24.5	7.1	5.4	387	199	34	81
Minimum.....	17.5	9.8	2.6	2.4	236	106	3	35
Mean.....	22.0	17.1	3.9	3.4	353	169	18	56
July 1984								
Maximum.....	28.2	24.3	13.2	3.9	377	200	53	72
Minimum.....	20.1	6.1	4.4	1.8	198	98	-1	26
Mean.....	25.1	15.4	9.1	2.9	290	144	20	49

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE F--Continued								
<u>August 1984</u>								
Maximum.....	27.2	23.5	15.2	4.7	361	203	33	62
Minimum.....	20.5	2.7	3.6	1.6	115	35	-11	16
Mean.....	24.5	16.1	7.7	2.9	283	145	19	43
<u>September 1984</u>								
Maximum.....	27.3	21.4	10.2	4.6	294	152	20	66
Minimum.....	14.7	10.6	2.4	1.8	177	81	0	28
Mean.....	21.8	15.3	5.6	3.0	248	120	11	46
<u>October 1984</u>								
Maximum.....	18.6	13.5	6.2	6.6	232	133	21	56
Minimum.....	5.4	3.9	1.7	1.8	113	44	-8	18
Mean.....	11.5	8.1	3.3	3.0	193	87	8	37
<u>November 1984</u>								
Maximum.....	12.8	9.5	5.8	4.8	180	85	19	45
Minimum.....	-0.9	.5	1.9	1.2	21	3	-16	4
Mean.....	5.5	4.2	3.5	2.5	132	64	4	25
<u>December 1984</u>								
Maximum.....	6.7	3.7	6.3	8.1	137	83	17	23
Minimum.....	-9.7	.3	1.6	0.8	29	9	-18	4
Mean.....	0.0	1.5	3.8	2.1	102	46	-1	13
<u>January 1985</u>								
Maximum.....	6.1	5.7	4.9	6.1	168	96	28	29
Minimum.....	-1.1	.5	1.4	1.2	13	3	-3	2
Mean.....	2.2	2.9	3.0	2.9	128	63	11	19
<u>February 1985</u>								
Maximum.....	11.5	8.3	4.1	8.0	219	100	19	45
Minimum.....	-2.4	1.0	1.4	1.2	62	26	-10	10
Mean.....	5.3	5.4	2.4	2.9	179	79	11	32
<u>March 1985</u>								
Maximum.....	14.1	9.8	4.3	6.6	283	154	32	34
Minimum.....	2.2	3.8	1.3	2.2	135	54	-8	12
Mean.....	7.3	6.2	2.4	3.9	226	116	11	22

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE F--Continued								
April 1985								
Maximum.....	19.5	15.2	4.9	8.4	334	181	35	54
Minimum.....	8.7	5.5	1.7	2.3	261	132	0	19
Mean.....	15.7	11.7	3.2	3.2	305	162	22	41
May 1985								
Maximum.....	22.5	17.4	4.1	5.0	375	207	31	57
Minimum.....	14.4	10.0	2.3	2.2	292	127	10	33
Mean.....	19.1	14.6	3.2	3.4	338	186	25	46
June 1985								
Maximum.....	28.8	26.6	8.0	3.3	375	229	37	74
Minimum.....	12.8	5.6	2.9	2.2	174	100	3	22
Mean.....	24.9	21.1	4.4	2.8	345	195	28	61
July 1985								
Maximum.....	30.2	29.7	13.0	4.4	373	206	30	74
Minimum.....	22.5	7.5	3.1	2.2	230	122	9	35
Mean.....	27.0	21.8	5.9	3.0	319	182	24	56
August 1985								
Maximum.....	26.5	23.7	4.8	4.1	347	202	25	59
Minimum.....	21.1	16.9	2.8	2.2	300	170	16	43
Mean.....	24.7	21.2	3.6	2.9	326	184	21	53
September 1985								
Maximum.....	24.2	19.2	9.0	4.5	304	164	24	60
Minimum.....	12.3	3.1	2.9	2.1	99	24	-9	15
Mean.....	17.4	11.7	4.4	2.9	248	126	15	37
October 1985								
Maximum.....	21.6	17.5	4.2	5.6	240	121	18	70
Minimum.....	4.7	3.8	1.9	1.5	78	10	-17	13
Mean.....	13.2	9.9	3.1	3.0	196	90	7	45

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE L								
<u>December 1983</u>								
Maximum.....	5.7	3.5	5.1	4.0	131	50	21	21
Minimum.....	-0.4	1.5	3.5	1.4	85	20	3	10
Mean.....	3.3	2.3	4.3	2.0	115	38	14	16
<u>March 1984</u>								
Maximum.....	13.7	9.2	4.5	7.1	287	146	35	58
Minimum.....	5.5	4.8	2.1	1.9	203	83	-4	23
Mean.....	9.6	7.2	2.8	3.7	250	120	12	41
<u>April 1984</u>								
Maximum.....	17.5	13.3	4.4	6.4	333	184	36	130
Minimum.....	5.5	5.4	1.9	2.3	249	132	8	58
Mean.....	12.1	9.2	2.8	3.9	301	161	24	99
<u>May 1984</u>								
Maximum.....	25.5	21.4	7.1	5.1	369	225	34	252
Minimum.....	16.3	11.1	2.3	2.4	239	149	15	171
Mean.....	21.8	16.7	4.0	3.5	345	196	27	216
<u>June 1984</u>								
Maximum.....	21.1	12.8	7.0	6.3	374	218	19	234
Minimum.....	19.1	10.8	4.4	3.4	226	130	6	207
Mean.....	19.9	12.2	5.6	4.4	325	193	15	221
<u>July 1984</u>								
Maximum.....	26.4	21.3	12.8	3.5	351	226	21	249
Minimum.....	19.4	6.3	3.3	1.8	185	121	-2	110
Mean.....	23.5	13.1	9.2	2.6	278	176	10	176
<u>August 1984</u>								
Maximum.....	27.0	23.7	12.1	5.1	348	203	21	163
Minimum.....	20.4	7.2	3.4	1.8	135	75	-7	78
Mean.....	22.9	14.5	7.3	2.7	291	173	13	117

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE L--Continued								
<u>September 1984</u>								
Maximum.....	23.0	15.1	9.3	5.3	263	142	12	80
Minimum.....	14.1	10.7	2.2	1.8	183	84	2	48
Mean.....	19.1	12.6	5.2	2.8	243	125	8	67
<u>October 1984</u>								
Maximum.....	17.1	12.2	5.8	5.0	237	145	9	34
Minimum.....	6.5	5.3	2.6	1.7	143	58	-3	14
Mean.....	12.5	8.4	3.9	2.7	199	96	4	23
<u>November 1984</u>								
Maximum.....	12.1	9.3	5.0	5.4	182	74	10	33
Minimum.....	-1.0	.4	1.9	1.3	15	0	-12	2
Mean.....	5.3	4.8	2.9	2.6	129	51	1	16
<u>December 1984</u>								
Maximum.....	4.4	3.9	5.2	8.7	140	69	3	24
Minimum.....	-13.3	.4	1.4	0.8	23	-1	-11	3
Mean.....	-2.1	1.5	3.1	2.1	100	37	-4	13
<u>January 1985</u>								
Maximum.....	9.4	7.7	3.9	6.3	168	85	7	35
Minimum.....	-4.3	.5	1.2	1.1	10	3	-7	3
Mean.....	1.8	3.4	2.6	2.7	133	45	1	22
<u>February 1985</u>								
Maximum.....	12.0	8.8	3.8	9.4	223	72	12	44
Minimum.....	-3.0	1.1	1.3	1.3	100	37	-7	10
Mean.....	4.8	5.3	2.3	3.0	179	57	5	31
<u>March 1985</u>								
Maximum.....	13.3	8.1	6.6	6.6	262	117	12	44
Minimum.....	2.0	4.4	1.2	1.8	138	41	-5	19
Mean.....	6.9	5.7	2.7	3.6	206	77	4	31

APPENDIX A.--Daily average maximum and minimum, and monthly average meteorological data, and latent-heat flux estimates by the Penman-combination method, December 1983 through October 1985, at sites C, F, and L--Continued

Month	Air temperature (°C)	Vapor density deficit (g/m <sup>3</sup> )	Vapor density (g/m <sup>3</sup> )	Windspeed (m/s)	Solar radiation (W/m <sup>2</sup> )	Net radiation (W/m <sup>2</sup> )	Soil-heat flux (W/m <sup>2</sup> )	Latent-heat flux (W/m <sup>2</sup> )
SITE L--Continued								
April 1985								
Maximum.....	17.8	13.3	4.8	6.2	337	172	22	150
Minimum.....	9.5	6.2	1.8	2.2	235	105	-2	82
Mean.....	13.1	9.2	3.4	3.7	311	154	12	113
May 1985								
Maximum.....	20.9	15.2	6.1	6.4	375	198	21	197
Minimum.....	12.9	7.1	2.3	2.1	216	146	6	125
Mean.....	18.1	12.8	3.8	3.7	344	180	15	172
June 1985								
Maximum.....	27.8	23.6	7.9	4.6	374	212	27	276
Minimum.....	9.3	5.2	3.2	1.9	170	96	1	102
Mean.....	23.2	18.1	5.2	2.8	347	192	19	231
July 1985								
Maximum.....	29.2	25.8	14.7	3.7	370	201	24	260
Minimum.....	22.6	6.1	3.6	2.0	218	112	0	126
Mean.....	26.0	17.6	8.5	2.6	299	166	16	197
August 1985								
Maximum.....	26.1	22.7	6.2	4.6	333	174	17	154
Minimum.....	19.8	15.8	3.0	2.1	295	151	10	124
Mean.....	23.5	19.3	4.1	2.8	314	161	15	142
September 1985								
Maximum.....	25.3	21.1	7.3	4.8	305	171	16	85
Minimum.....	8.0	2.2	2.7	1.8	116	51	-13	21
Mean.....	16.3	11.3	4.2	2.8	246	130	8	55
October 1985								
Maximum.....	20.4	16.6	4.1	7.6	243	114	12	53
Minimum.....	4.6	4.2	1.9	1.5	117	40	-9	11
Mean.....	12.9	9.8	3.0	3.3	202	90	5	34





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