# Estimates of Evapotranspiration in Alkaline Scrub and Meadow Communities of Owens Valley, California, Using the Bowen-Ratio, Eddy-Correlation, and Penman-Combination Methods

United States Geological Survey Water-Supply Paper 2370–E

Prepared in cooperation with Inyo County and the Los Angeles Department of Water and Power

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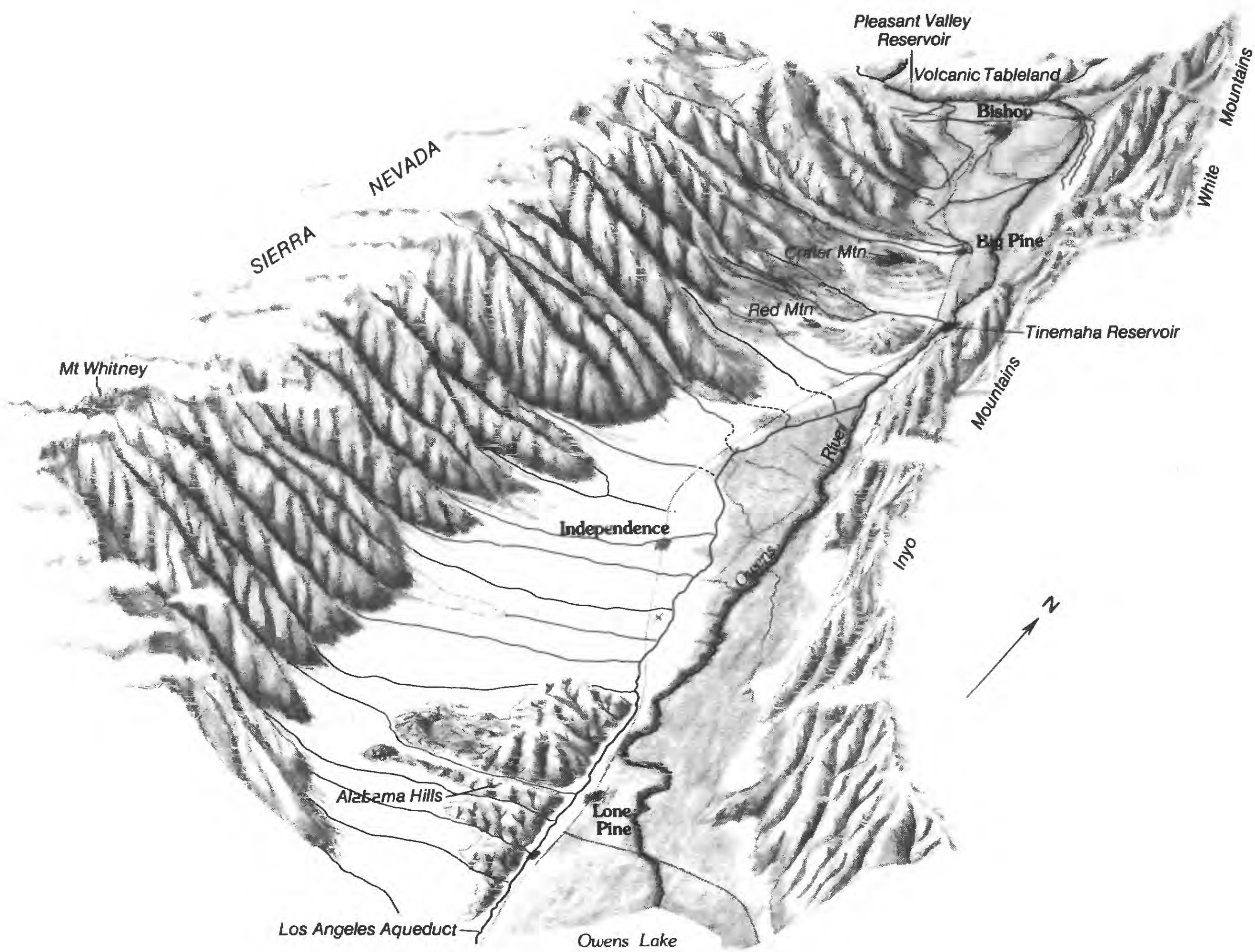
# ESTIMATES OF EVAPOTRANSPIRATION IN ALKALINE SCRUB AND MEADOW COMMUNITIES OF OWENS VALLEY, CALIFORNIA, USING THE BOWEN-RATIO, EDDY-CORRELATION, AND PENMAN-COMBINATION METHODS




Vertically exaggerated perspective and oblique view of Owens Valley, California, showing the dramatic change in topographic relief between the valley and surrounding mountains.

Chapter E

# Estimates of Evapotranspiration in Alkaline Scrub and Meadow Communities of Owens Valley, California, Using the Bowen-Ratio, Eddy-Correlation, and Penman-Combination Methods

By LOWELL F.W. DUELL, JR.

Prepared in cooperation with
Inyo County and the
Los Angeles Department of Water and Power

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2370

HYDROLOGY AND SOIL-WATER-PLANT RELATIONS IN OWENS VALLEY, CALIFORNIA

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director



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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 |
| $d/dV$ | Voltage gradient |
| $dT/dx$ | Temperature gradient in direction x |
| $d\rho_v/dV$ | Vapor-density voltage gradient |
| $d\rho_v/dz$ | 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 Kármán's constant |
| $N$ | 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 estimate |
| $T$ | Air temperature |
| $T_w$ | Wet-bulb temperature |
| $u$ | Mean windspeed at height $Z$ |
| $V$ | Hygrometer voltage output |
| $V_o$ | Unattenuated voltage output |
| $w$ | Vertical wind velocity |
| $x$ | Path length |
| $\overline{X}$ | 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...) |
| ' | Instantaneous deviation from the mean |
| $\overline{\phantom{x}}$ | Mean for a 30-minute period |

## CONVERSION FACTORS

For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

| Multiply | By | To obtain |
|---|---|---|
| *Area* | | |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |
| *Density* | | |
| grams per cubic meter ($g/m^3$) | 0.4370 | grains per cubic foot ($gr/ft^3$) |
| | $6.2428 \times 10^{-5}$ | pounds per cubic foot ($lb/ft^3$) |
| *Energy* | | |
| joule (J) | $9.4787 \times 10^{-5}$ | British thermal unit (Btu) |
| | 0.2388 | calorie (cal) |
| *Energy and Area Time* | | |
| watts per square meter ($W/m^2$) | $5.2895 \times 10^{-3}$ | British thermal units per square foot per minute [$(Btu/ft^2)/min$] |
| *Energy and Mass* | | |
| joules per gram (J/g) | 0.4303 | British thermal units per pound (Btu/lb) |
| *Length* | | |
| 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) |
| *Mass* | | |
| gram (g) | $2.205 \times 10^{-3}$ | pound (lb) |
| *Mass flux* | | |
| grams per square meter ($g/m^2$) | 17.71 | pounds per square foot per day [$(lb/ft^2)/d$] |
| *Power* | | |
| watt (W) | 3.412 | British thermal units per hour (Btu/h) |
| | $1.340 \times 10^{-3}$ | horsepower (hp) |
| | 0.2388 | calories per second (cal/s) |
| *Specific heat* | | |
| kilojoules per gram per kelvin [(kJ/g)K] | $2.388 \times 10^{-4}$ | British thermal units per pound per degree Fahrenheit [(Btu/lb)/°F] |
| *Pressure* | | |
| kilopascal (kPa) | 0.2953 | inches of mercury (in. Hg) |
| | 0.1450 | pound per square inch ($lb/in^2$) |
| | 10 | millibar (mbar) |
| *Temperature* | | |
| degree Celsius (°C) | 1.8 °C+32 | degree Fahrenheit (°F) |
| kelvin (K) | (K−273.15)1.8+32 | degree Fahrenheit (°F) |
| *Velocity or Rate* | | |
| meter per second (m/s) | 2.237 | mile per hour (mi/h) |
| *Volume* | | |
| cubic meter ($m^3$) | $8.107 \times 10^{-4}$ | 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 Sea Level Datum of 1929.

# Estimates of Evapotranspiration in Alkaline Scrub and Meadow Communities of Owens Valley, California, Using the Bowen-Ratio, Eddy-Correlation, and Penman-Combination Methods

*By* Lowell F.W. Duell, Jr.

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 with 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 of 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 301 millimeters at a low-density scrub site to 1,137 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. Geology 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.
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. Soil water and vegetation responses to precipitation and changes in depth to ground water in Owens Valley, California.

Manuscript approved for publication, January 28, 1988.

H. Numerical evaluation of the hydrologic system and selected water-management alternatives 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 also 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. It 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 this 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. Snyder 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; and (3) Leonard W. Jolley and Fred A. Fischer, U.S. Soil Conservation Service. U.S. Geological Survey personnel who assisted at various times and at 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.

# DESCRIPTION OF THE 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 $km^2$. The length of the study area within the valley is approximately 80 km. The width of the study area ranges from about 15 km in the north to 8 km in the region between Big Pine and Independence in the south. The study area includes about 900 $km^2$ of the valley floor.

The valley floor between Independence and Laws 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 rises 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, 120 mm at site F, and 70 mm at site L. Monthly precipitation totals recorded during this study from November 1983 to October 1985 at sites C, F, and L are shown in figure 3. The largest single 1-day rain event during this study was 27 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.

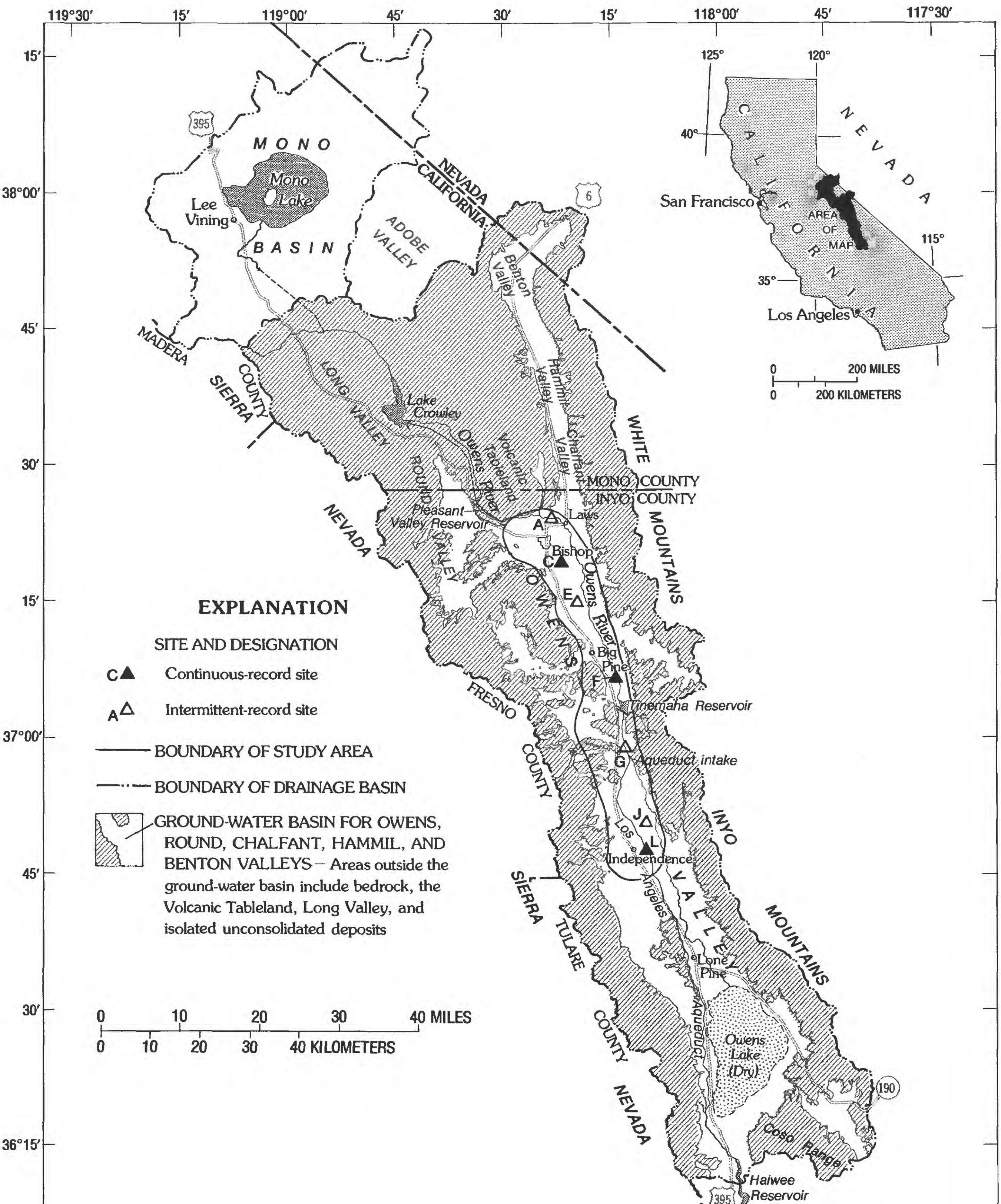


**Figure 1.** Location of study area and study sites.

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 Ocean 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).

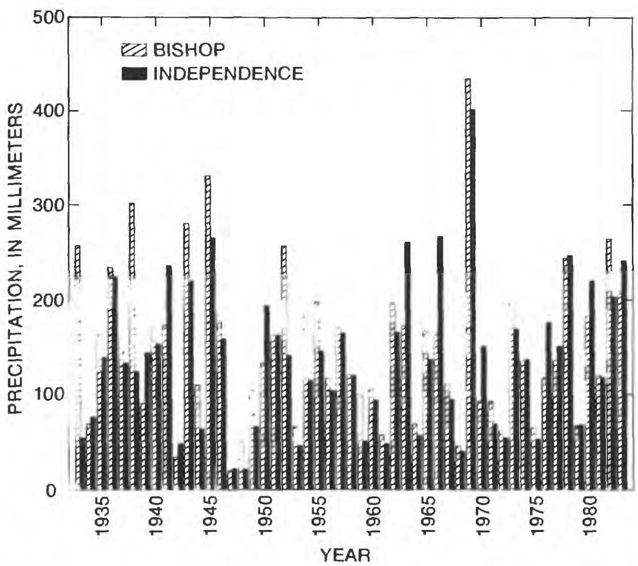


**Figure 2.** Comparison of annual precipitation from 1933 to 1983 at Bishop and Independence National Weather Bureau stations (Los Angeles Department of Water and Power, written commun., 1984).

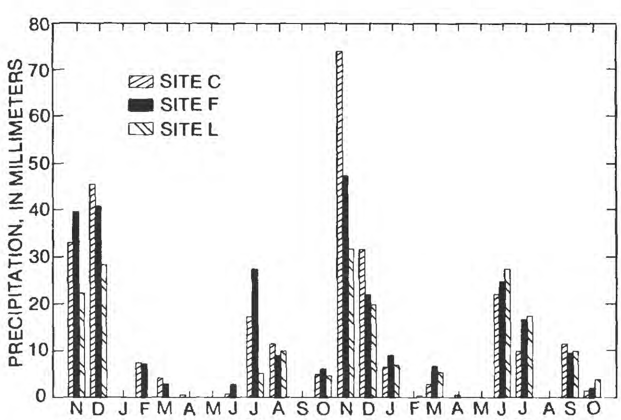


**Figure 3.** Comparison of monthly precipitation at sites C, F, and L, November 1983–October 1985.

The average monthly air temperature at sites C, F, and L for 1984–85 differed by no more than 6 °C from historical data for 1895–1910 and 1933–81 at Independence and 1933–81 at Bishop. 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 by 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.

Wind direction in the valley is generally from the south or north. This is the result of the local mountain fronts

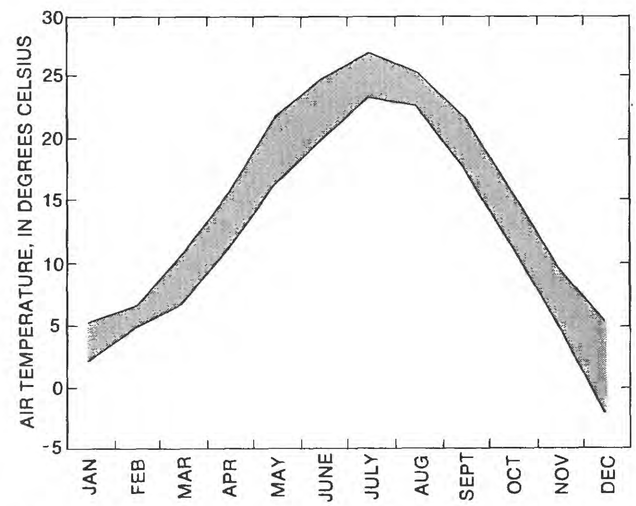


**Figure 4.** Range of average monthly air temperature for study sites C, F, and L, 1984–85, and Bishop and Independence National Weather Bureau stations, 1895–1981 (Lee, 1912; Los Angeles Department of Water and Power, written commun., 1984; this study).

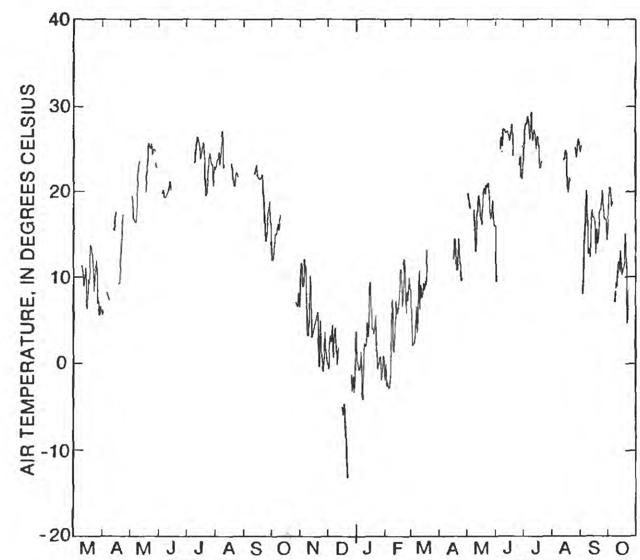


**Figure 5.** Daily average air temperature at site L, March 1984–October 1985.

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 windspeed at site F is shown in figure 6. High windspeeds can occur any time during the year but generally take place during a winter or spring storm.

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 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 g/m$^3$ (many times during winter months) to 17.4 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.

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 the varying cloud cover and the 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 W/m$^2$ at site C on June 12, 1984.

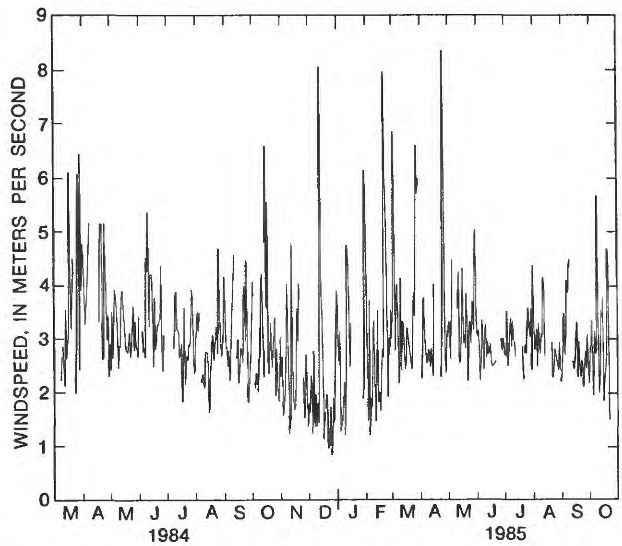


Figure 6. Daily average windspeed at site F, March 1984–October 1985.

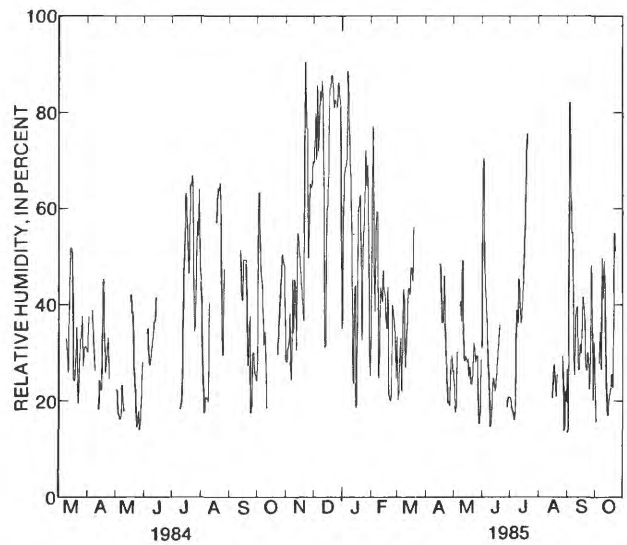


Figure 8. Daily average relative humidity at site L, March 1984–October 1985.

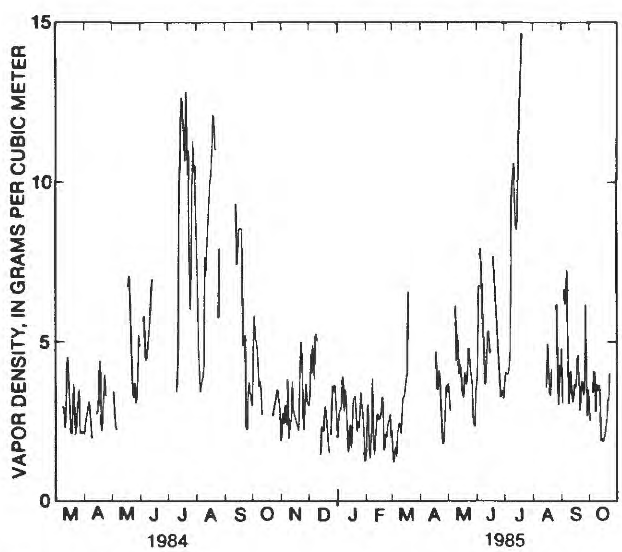


Figure 7. Daily average vapor density at site L, March 1984–October 1985.

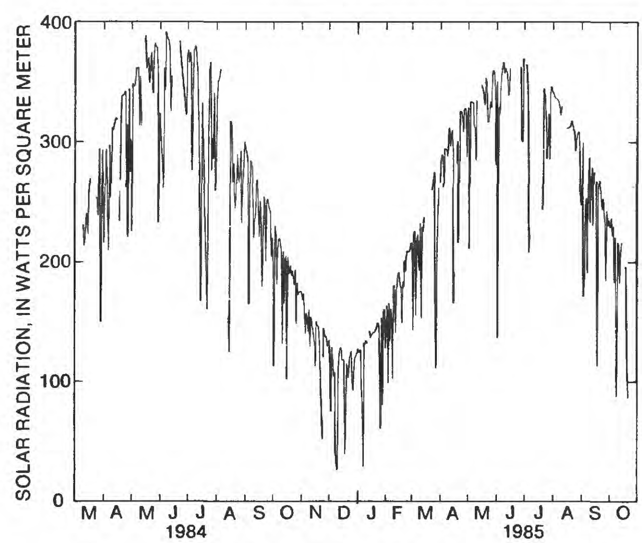


Figure 9. Daily average solar radiation at site C, March 1984–October 1985.

## 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, 1989). 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 both water levels in shallow wells in the vicinity of phreatophyte communities and 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 most common plant types of the study sites 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-grained loamy texture.

**Table 1.** Most common vegetation found at study sites

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

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

## 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 deposits, and formations derived from volcanic materials.

Hollett and others (1989) described 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.

**Table 2.** Vegetation characteristics and water-level data for 1984 at 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 vegetative cover (percent) | Average plant height (meters) | Most common plant type | Range of water level (meters below land-surface datum) |
|---|---|---|---|---|
| A | 42 | 0.3-0.6 | SPAI<br>SAKAT<br>BAHY[1]<br>DISPS2[1] | 3.2-4.7 |
| C | 35 | 0.5 | DISPS2<br>CHNA2<br>SPAI<br>ATTO<br>SAVE4 | 3.1-3.5 |
| E | 26 | 0.3-0.5 | CHNA2<br>SPAI<br>EPNE<br>ARTRT<br>DISPS2[1]<br>SAVE4[1] | 3.1-3.3 |
| F | 24 | 0.3-0.5 | DISPS2<br>SAVE4<br>SPAI<br>ATTO | 2.4-2.7 |
| G | 33 | 0.3-0.5 | DISPS2<br>SPAI<br>CHNA2<br>SAVE4 | 2.2-2.7 |
| J | 50 | 0.5-0.6 | ATTO<br>SPAI<br>CHNA2<br>DISPS2<br>GLLE3 | 1.4-2.2 |
| L | 72 | 0.3-0.5 | DISPS2<br>SPAI<br>JUBA | 0.0-1.2 |

[1]Percentage of composition approximately the same; therefore equally dominant.

## 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

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

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 August 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); they compared results with 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 with 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 are 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

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

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,

where

$$\rho_a=\rho \frac{\text{station barometric pressure, in kilopascals}}{\text{sea-level barometric pressure, in kilopascals}} \quad ; \tag{3}$$

$\rho$ 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:

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

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

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

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

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

where

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

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

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

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

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

where

$\rho_v$ is the vapor density, in grams per cubic meter;
$\rho'_v$ is the saturated vapor density, in grams per cubic meter;
$T$ is the air temperature in degrees Celsius; 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)

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

where

$R$ is the water-vapor specific gas constant, equal to $4.62\times10^{-4}$ (kJ/g)/K.

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. 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 both the upward flux of reflected solar radiation and the 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 $\mu$V/(W/m$^2$), an internal resistance of 200 $\Omega$ (ohms), and a time constant of approximately 12 seconds.

The net radiometer scans a conical area both upward and downward with a field of view of about 65°. Towers, masts, and other objects can cast shadows either on 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 Eppley 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 Eppley Precision Spectral Pyranometers and two Eppley 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 with those 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.

*Soil-heat-flux plate.*—The soil-heat-flux plates used in this study, made by Melcor Inc. and developed from thermopile heat pumps used commercially as cooling devices, 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 with 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 because it was assumed that errors in soil-heat flux and the other terms of the energy budget canceled each other during a 24-hour period.

*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-V 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 non-linear thermistors used for measuring the wet- and dry-bulb temperatures. The major error component was the ±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 that 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 were presented by Simpson and Duell (1984).

At the start of each 15-minute cycle for collecting psychrometer data, all power to the system was off. After


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

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 that 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 turned 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.

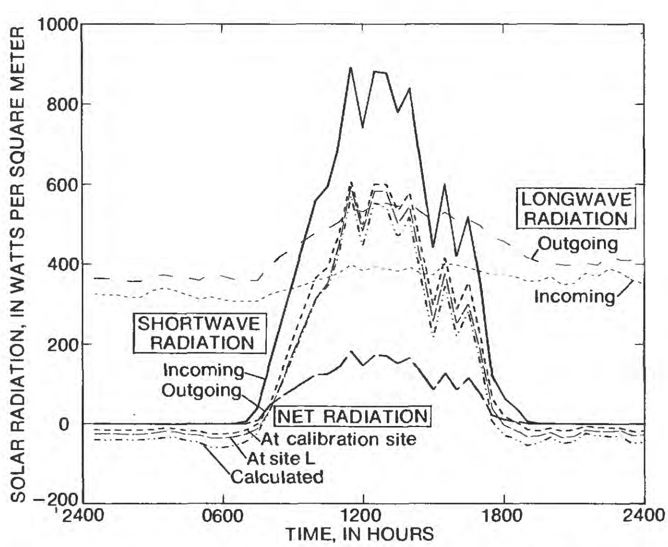


**Figure 11.** Comparison of components of net radiation, calculated net radiation, and measured net radiation at site L, September 18, 1984.

## 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 adjustments to sunrise, sunset, and nighttime data were made when the one-half-hour average appeared erroneous. Other data generally were not cor-


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

rected. The adjustment procedure, similar to that used by McNaughton and Black (1973), consisted of interpolating between the before and after one-half-hour averages, 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.

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 the 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$^3$ at site C and 0.20 g/m$^3$ at site F, whereas gradients at site L commonly ranged from 0.5 to 1.0 g/m$^3$. In determining the Bowen ratio (eq 6), errors in small vapor-density gradients can produce large errors in the Bowen ratio because the vapor-density gradient is in the denominator. When low temperatures 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 fluxes were similar in magnitude, with April having a longer amplitude, probably due to the longer daylight interval in that month. 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 occurs in May (fig. 13). A seasonal trend for *ET*

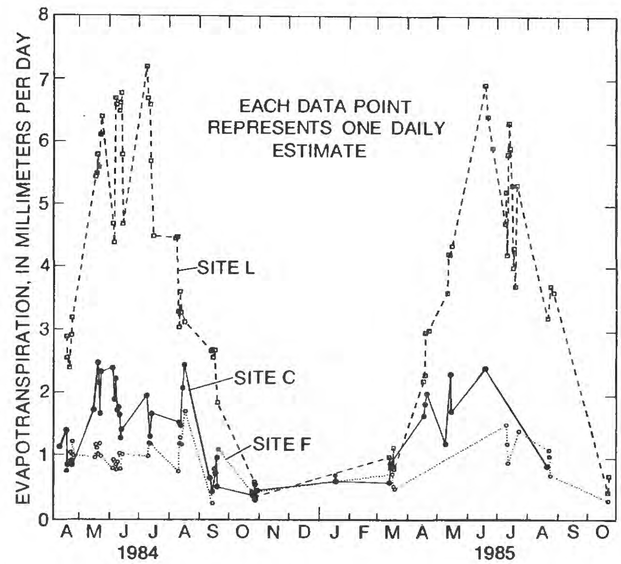


**Figure 13.** Daily evapotranspiration estimated by Bowen-ratio method for sites C, F, and L, April 1984–October 1985.

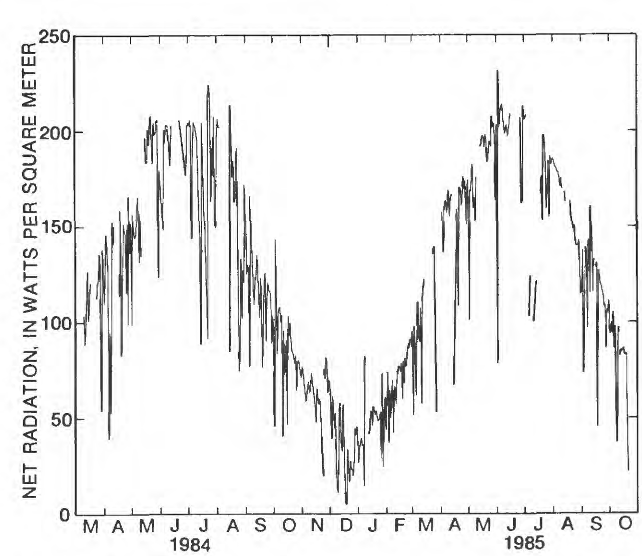


**Figure 14.** Daily average net radiation at site C, March 1984–October 1985.

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 started to come 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 as 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).

## 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 is 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 by Duell (1985).

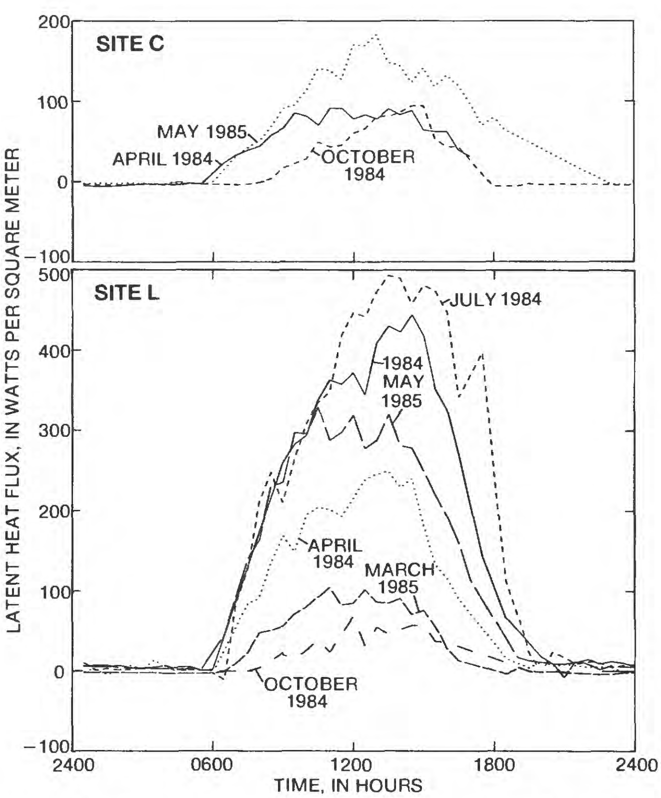


**Figure 15.** Comparison of average 24-hour latent-heat flux estimated for selected months by Bowen-ratio method at sites C and L.

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)

$$\lambda E=\overline{\rho_v{}'w'} \tag{11}$$

and

$$H=\rho_a C_p \overline{w'T'} \quad , \tag{12}$$

where

$'$ is the instantaneous deviation from the mean;

$\overline{\phantom{x}}$ is the mean 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 Campbell Scientific Inc. for the eddy-correlation method. Theoretically, fluxes (latent- plus sensible-heat flux) equal the energy budget (net radiation minus soil-heat flux). However, in field conditions the fluxes did not equal the energy budget, which thus indicates 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:

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

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:

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

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 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.

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:

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

where

- $V$ is the hygrometer voltage output, in millivolts;
- $V_o$ is the unattenuated voltage output, in millivolts;
- $K$ is the attenuation coefficient, in square meters per gram; and
- $x$ is the path length, in meters.

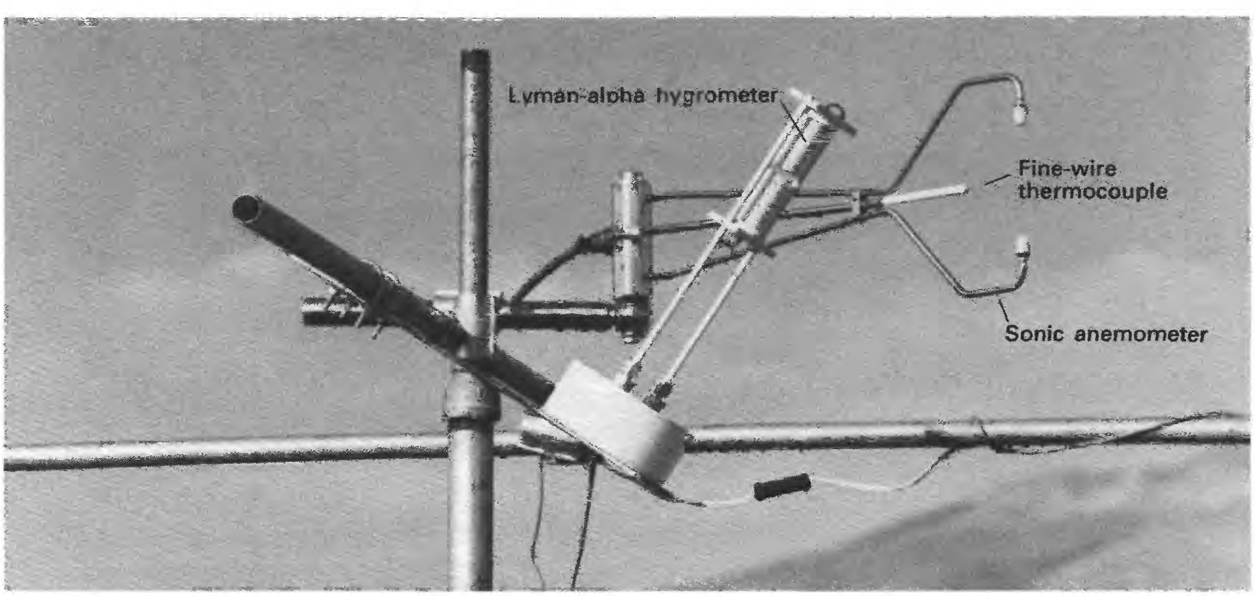


**Figure 16.** Eddy-correlation instruments (height approximately 3 m above land surface).

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

$$Kx=A+B\rho_v \quad , \tag{16}$$

where

$A$ and $B$ are experimentally determined coefficients.

Substituting equation 16 into equation 15:

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

Upon taking the logarithm of both sides and rearranging:

$$\ln V=\ln V_o - A\rho_v - B(\rho_v)^2 \quad . \tag{18}$$

Then differentiating equation 18 with respect to $V$:

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

where

$d/dV$ 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

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

where

$d\rho_v/dV$ is the vapor-density voltage gradient.

Solving equation 19 for $d\rho_v/dV$:

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

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 by 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 $B$ in 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, which measures the phase shift generated by convected translation of emitted sound waves 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 the 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 μm 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 is 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.

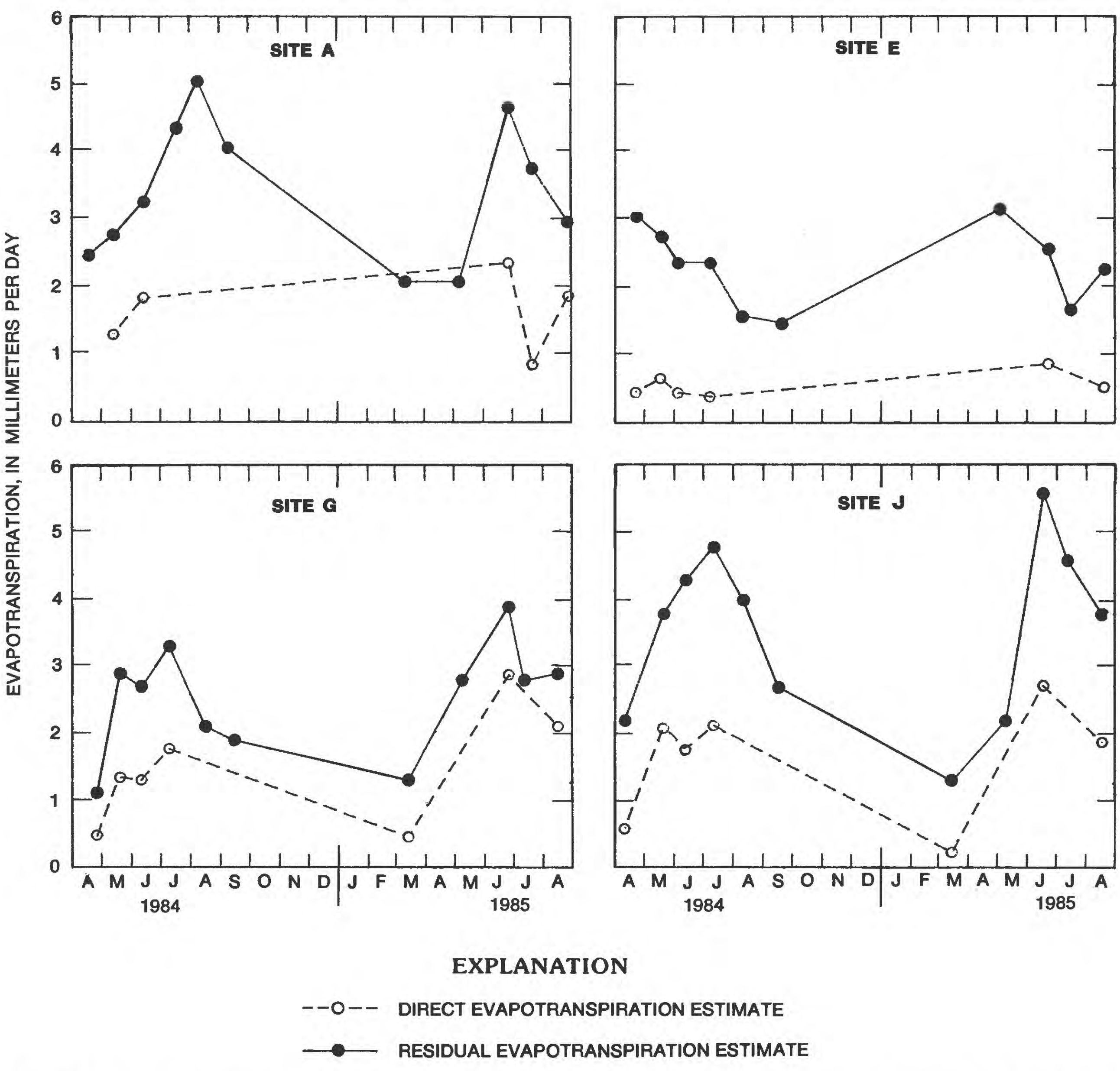


**Figure 17.** Monthly average direct and residual evapotranspiration estimated by eddy-correlation method at sites A, E, G, and J, April 1984–August 1985.

These data indicate that direct *ET* represents minimum estimates, whereas 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 is 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 June and 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.

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:

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

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, p. 150), giving

$$S = 0.337569 + 0.02067T + 0.000427T^2 + 0.0000117T^3, \qquad (22)$$

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

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

where

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

  $\log d = 0.9793 \log h - 0.1536$ (Stanhill, 1969, p. 513); (24)
- $h$ is the average crop height, in meters, multiplied by the percentage of vegetative cover;
- $Z_m$ is the roughness parameter for momentum, equal to $0.13h$, in meters;
- $Z_h$ is the roughness parameter for heat transfer, equal to $0.2Z_m$, in meters;
- $k$ is von Kármán'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 in the Penman-combination method (Montieth, 1973, p. 175):

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

where

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

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, by using the latent-heat flux estimated from the Bowen-ratio method and rearranging equations 25 and 26, we can calculate the vapor-diffusion resistance by

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

### 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.

*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):

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

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:

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

where

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

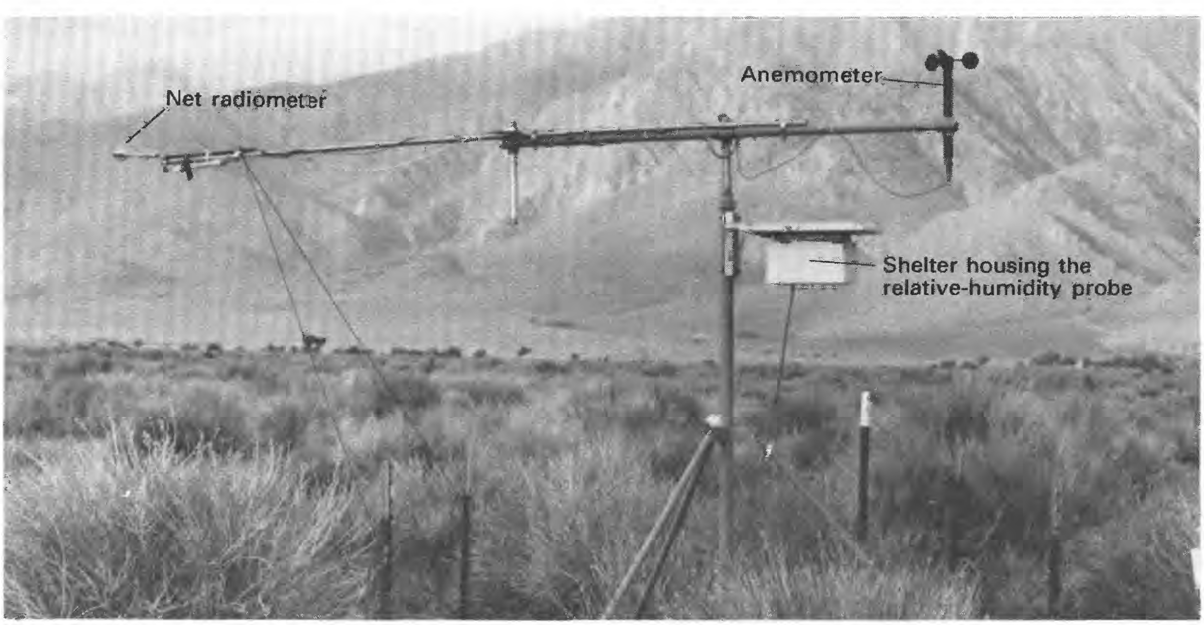


**Figure 18.** Penman-combination instruments at site C. (Approximate height of net radiometer is 2 m above land surface.)

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 occurred 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 with 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 by a factor of 5 to 10 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 with 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 the 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 also could 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 with 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

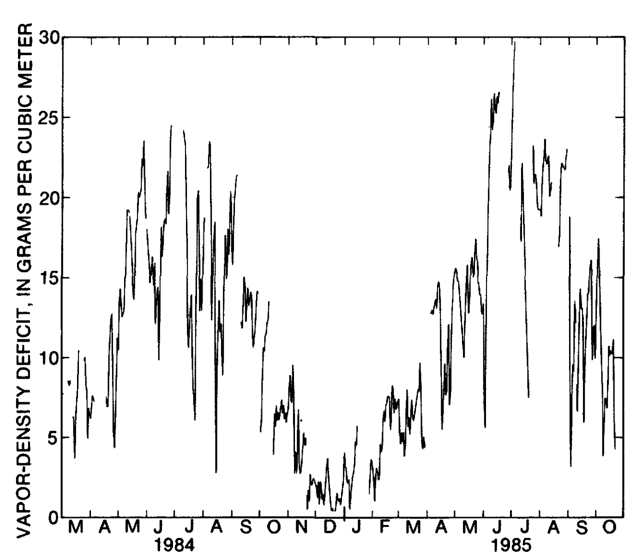


**Figure 19.** Daily average vapor-density deficit at site F, March 1984–October 1985.

canopy surface. If much of the surface is dry bare soil, then a much larger surface is available for heat diffusion than for 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 and 1985 when heat- and vapor-diffusion resistances 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.

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 owing 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, or a mean-weighted average was 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 1,072 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 seen 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 *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 was 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 that 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.

The meteorological data collected for use in the Penman-combination method provided a more complete record of the microclimate at sites C, F, and L than did that for 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)

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

[$\overline{X}$, algebraic 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 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\overline{X}$ | Range | $\sigma$ | $N$ | $\overline{X}$ | Range | $\sigma$ | $N$ | $\overline{X}$ | Range | $\sigma$ | $N$ |
| *1983* | | | | | | | | | | | | |
| December | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- |
| *1984* | | | | | | | | | | | | |
| January | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- |
| February | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- |
| March | [2]620 | -- | -- | -- | [2]680 | -- | -- | -- | [2]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 | 1,072 | 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 | 1,045 | 304-2,153 | 490 | 37 |
| November | [3]540 | -- | -- | -- | [3]410 | -- | -- | -- | [3]700 | -- | -- | -- |
| December | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- |
| *1985* | | | | | | | | | | | | |
| January | 360 | 171-681 | 120 | 39 | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- |
| February | [1]360 | -- | -- | -- | [1]360 | -- | -- | -- | [1]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 | [3]770 | -- | -- | -- | 180 | 46-643 | 102 | 87 |
| May | 499 | 152-1,384 | 258 | 40 | [3]860 | -- | -- | -- | 141 | 62-509 | 63 | 76 |
| June | 1,018 | 247-2,843 | 853 | 14 | [3]950 | -- | -- | -- | 105 | 42-268 | 55 | 32 |
| July | 990 | 581-1,743 | 361 | 8 | 1,043 | 221-3,093 | 674 | 18 | 127 | 61-354 | 57 | 98 |
| August | [3]940 | -- | -- | -- | 1,057 | 313-2,642 | 751 | 12 | 262 | 50-860 | 132 | 44 |
| September | [4]910 | -- | -- | -- | [4]780 | -- | -- | -- | [3]530 | -- | -- | -- |
| October | [4]720 | -- | -- | -- | [4]460 | -- | -- | -- | 702 | 325-1,605 | 327 | 22 |

[1]Winter data for all sites.
[2]1985 data.
[3]Data interpolated from preceding and following months.
[4]1984 data.

and daily data indicates how *ET* was correlated to the 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 did 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.

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 temperatures, the most easily measured data, are 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 using 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 also can be used to indicate the effect meteorological data (appendix A) and vapor-diffusion resistance (table 3) have on calculating *ET*. In 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 one-half-hour latent-heat fluxes 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 December 1984 are similar, but the monthly average meteorological data (appendix A) were different. In December 1983 less energy was available than in 1984, but because the vapor-density deficit was mostly higher, latent-heat flux was similar. At site C, the July 1984 and July 1985 curves were similar because a lower vapor-diffusion-resistance constant was used in 1984 due to a lower vapor-density deficit in that year. At site F, the August 1984 monthly average 24-hour latent-heat-flux curve indicates lower latent-heat flux than in 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.

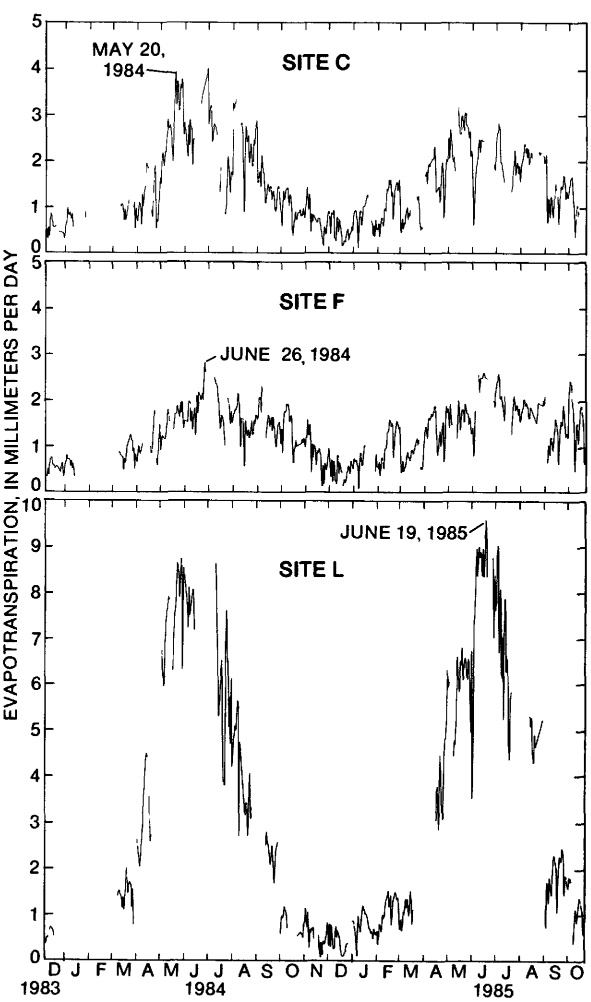


**Figure 20.** Daily evapotranspiration estimated by Penman-combination method at sites C, F, and L, December 1983–October 1985.

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

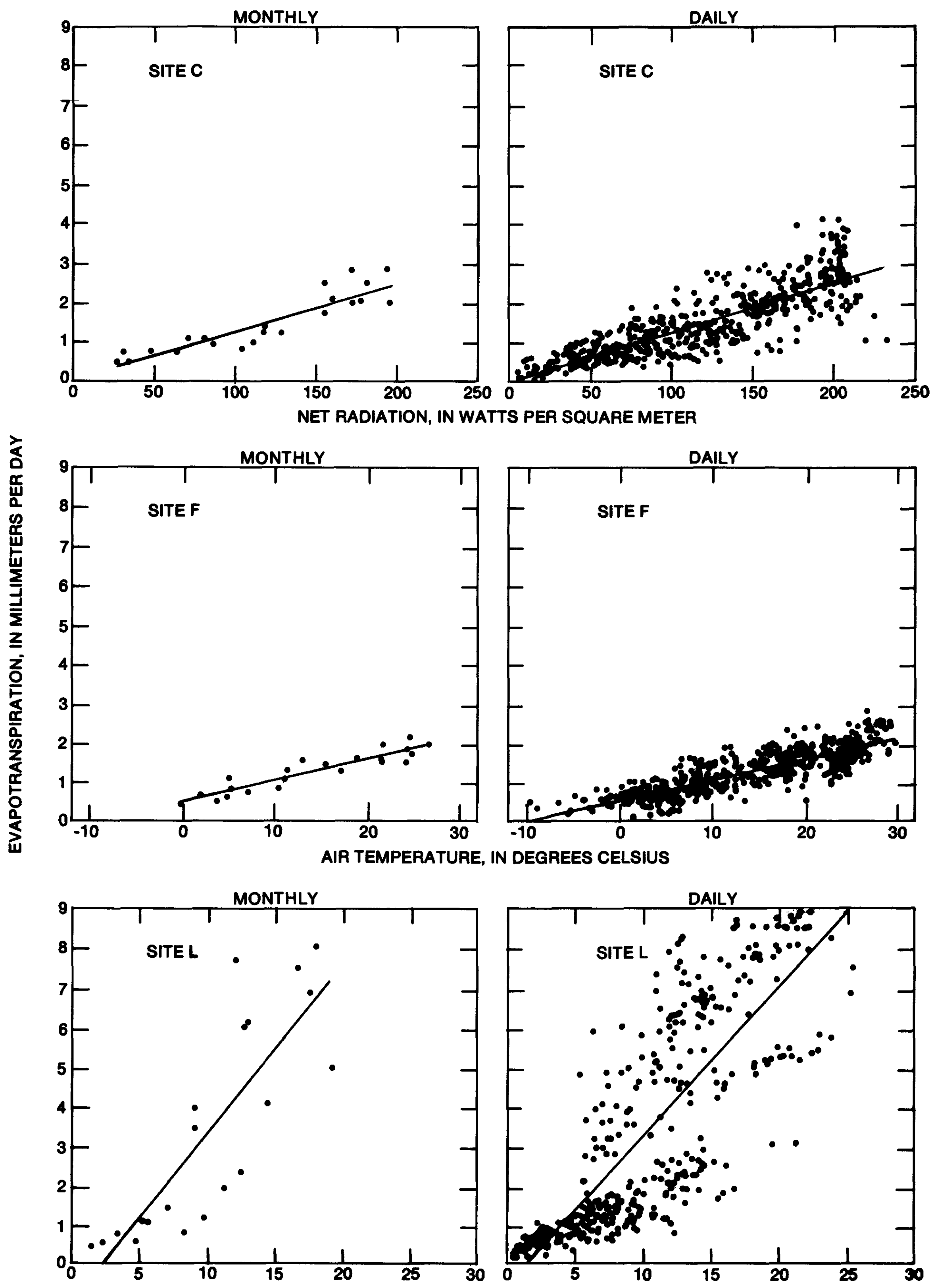


**Figure 21.** Linear regression of monthly and daily evapotranspiration estimated by Penman-combination method for net radiation at site C, for air temperature at site F, and for vapor-density deficit at site L.

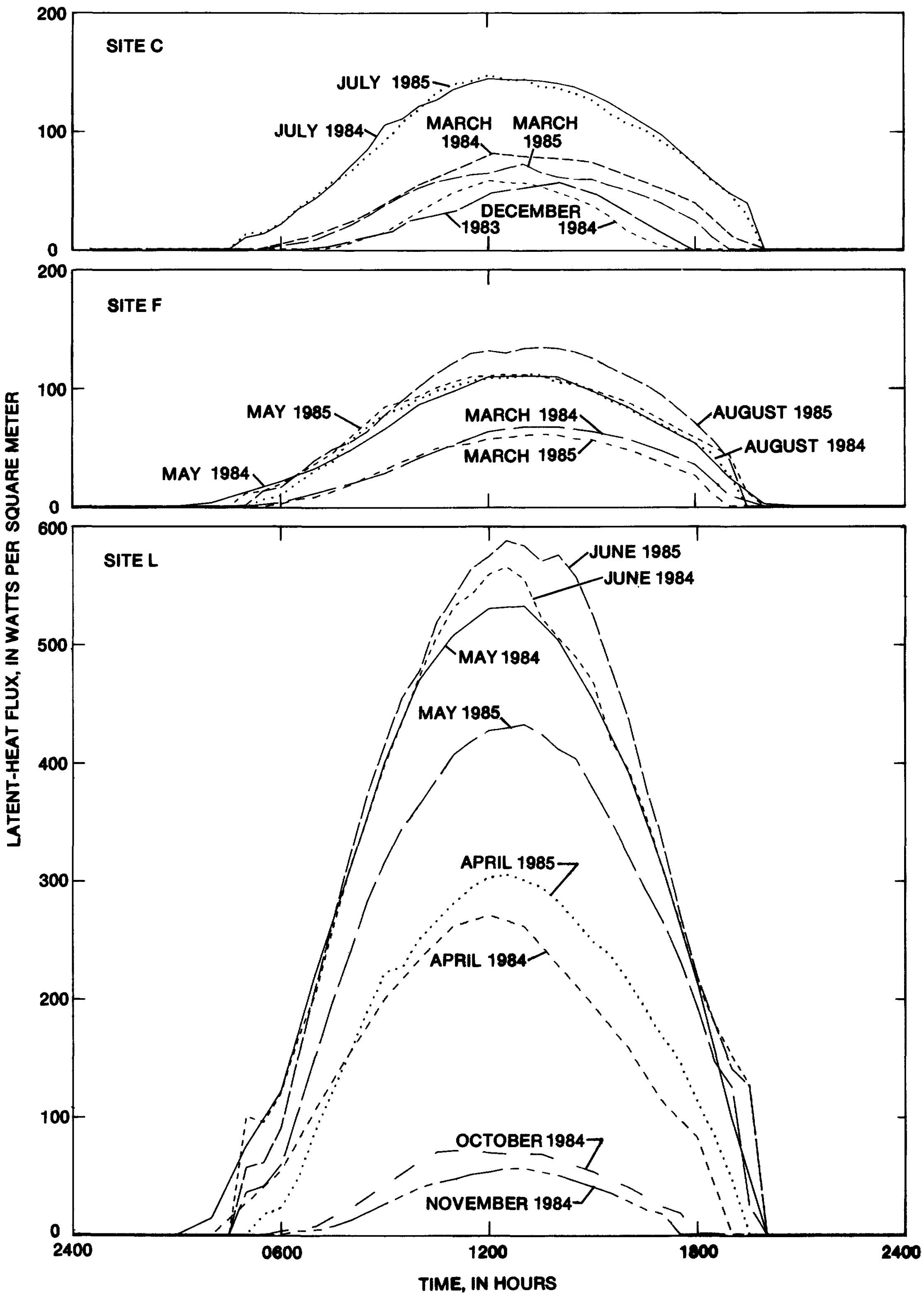


**Figure 22.** Comparison of average 24-hour latent-heat flux estimated by Penman-combination method for selected months at sites C, F, and L.

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

| Date | Estimated evapotranspiration, in millimeters | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bowen ratio | | | Residual eddy correlation (direct eddy correlation in parentheses) | | | | Penman combination | | |
| | Site C | Site F | Site L | Site A | Site E | Site G | Site J | Site C | Site F | Site L |
| *1984* | | | | | | | | | | |
| January | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | 24 | 19 | [2]24 |
| February | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | [2]31 | [2]31 | [2]30 |
| March | [3]36 | [3]29 | [3]56 | [3]53 | [3]60 | [3]32 | [3]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 | [1]25 | [1]32 | [1]32 | [1]32 | [1]32 | 30 | 41 | 25 |
| November | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | [1]22 | 23 | 26 | 17 |
| December | [1]14 | [1]14 | [1]14 | [1]14 | [1]14 | [1]14 | [1]14 | 15 | 14 | 14 |
| Total | 442 | 316 | 975 | 855 | 596 | 580 | 838 | 555 | 446 | 1,120 |
| *1985* | | | | | | | | | | |
| January | 22 | [1]23 | [1]23 | [1]23 | [1]23 | [1]23 | [1]23 | 25 | 21 | 24 |
| February | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | [1]31 | 31 | 31 | 30 |
| March | 22 | 19 | 28 | 65 | [1]60 | 40 (14) | 40 (7) | 26 | 24 | 33 |
| April | 36 | [4]27 | 85 | [3]65 | [3]80 | [3]64 | [3]54 | 53 | 44 | 120 |
| May | 62 | [4]34 | 124 | 65 | 99 | 87 | 68 | 79 | 50 | 188 |
| June | 57 | [4]33 | 177 | 141 (71) | 78 (27) | 117 (87) | 168 (82) | 61 | 64 | 244 |
| July | [3]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 | [4]27 | [4]21 | [4]69 | [4]123 | [4]45 | [4]57 | [4]81 | 35 | 39 | 58 |
| October | [4]19 | 9 | 17 | [1]40 | [1]40 | [1]40 | [1]40 | 35 | 49 | 37 |
| Total | [5]378 | [5]301 | [5]841 | [5]800 | [5]616 | [5]672 | [5]802 | [5]510 | [5]480 | [5]1,137 |

[1]Data estimated from Penman-combination method data.
[2]1985 data.
[3]Data interpolated from preceding and following months.
[4]1984 data.
[5]Estimated annual total includes November and December 1984 data.

## 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

**Table 6.** Vegetation characteristics, water-level and precipitation data, and range in evapotranspiration estimates at 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: Common name | Most common plant type: Composition of total vegetation (percent) | Total vegetative cover (percent) | Range of water levels for 1984 (meters below land surface) | Annual precipitation for 1984 (millimeters) | Annual evapotranspiration estimates for 1984-85 (millimeters): Maximum | Minimum | Mean |
|---|---|---|---|---|---|---|---|---|---|
| A | Alkali meadow | Alkali sacaton<br>Russian thistle | 43<br>22 | 42 | 3.2-4.7 | -- | 855 | 800 | 828 |
| C | Rabbitbrush meadow | Saltgrass<br>Rubber rabbitbrush | 34<br>25 | 35 | 3.1-3.5 | 150 | 555 | 378 | 471 |
| E | Desert sink scrub | Rubber rabbitbrush<br>Alkali sacaton<br>Mormon tea | 24<br>23<br>8 | 26 | 3.1-3.3 | -- | 616 | 596 | 606 |
| F | Desert sink scrub | Saltgrass<br>Greasewood | 34<br>27 | 24 | 2.4-2.7 | 160 | 480 | 301 | 385 |
| G | Alkali meadow | Saltgrass<br>Alkali sacaton<br>Rubber rabbitbrush | 30<br>13<br>9 | 33 | 2.2-2.7 | -- | 672 | 580 | 626 |
| J | Alkali meadow | Nevada saltbush<br>Alkali sacaton<br>Rubber rabbitbrush | 29<br>21<br>16 | 50 | 1.4-2.2 | -- | 838 | 802 | 820 |
| L | Rush and sedge meadow | Saltgrass<br>Alkali sacaton<br>Baltic rush | 20<br>17<br>15 | 72 | 0.0-1.2 | 80 | 1,137 | 841 | 989 |

expected because the percentage of vegetation cover (table 2) at sites A, E, G, and J ranged within the percentage of 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 of vegetation cover at sites E and G was less than at site C (table 2). These results probably were caused by the different methods used rather than by 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 by the estimates of the vapor-diffusion-resistance constant. In some cases it appears that 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.

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 (1987) 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 indicate that the most common plant types of 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 were 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 the 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 1 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±2.6 in May, 20.5±1 in June, and 18.2±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.

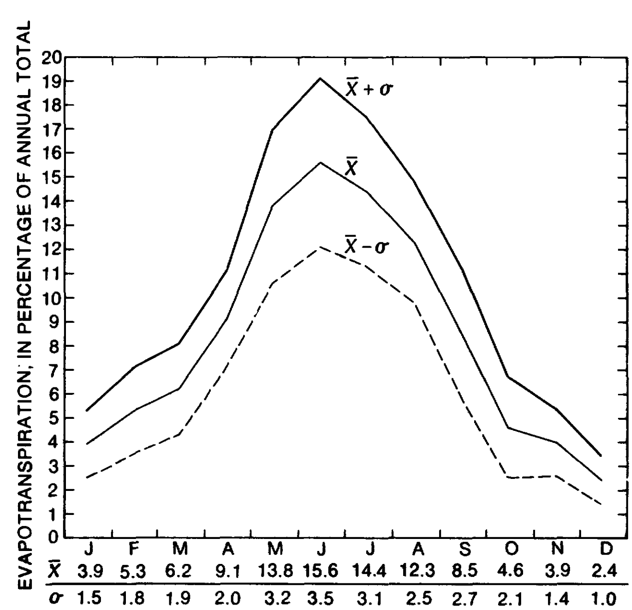


**Figure 23.** Monthly percentage ($\bar{X}$, algebraic mean; $\sigma$, standard deviation) of average annual evapotranspiration for 1984–85.

# 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 m 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 allowed 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.

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 allowed 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 the Penman-combination estimates generally higher, than the Bowen-ratio and residual eddy-correlation estimates. Latent-heat-flux estimates by the Bowen-ratio and residual eddy-correlation methods (fig. 25) at site L generally compare closely, whereas at sites C and F 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 $W/m^2$ at site L and less than 62 $W/m^2$ at sites C and F. Daily sensible-heat flux estimated by the eddy-correlation method was 3 $W/m^2$ at site L and greater than 65 $W/m^2$ at sites C and F.

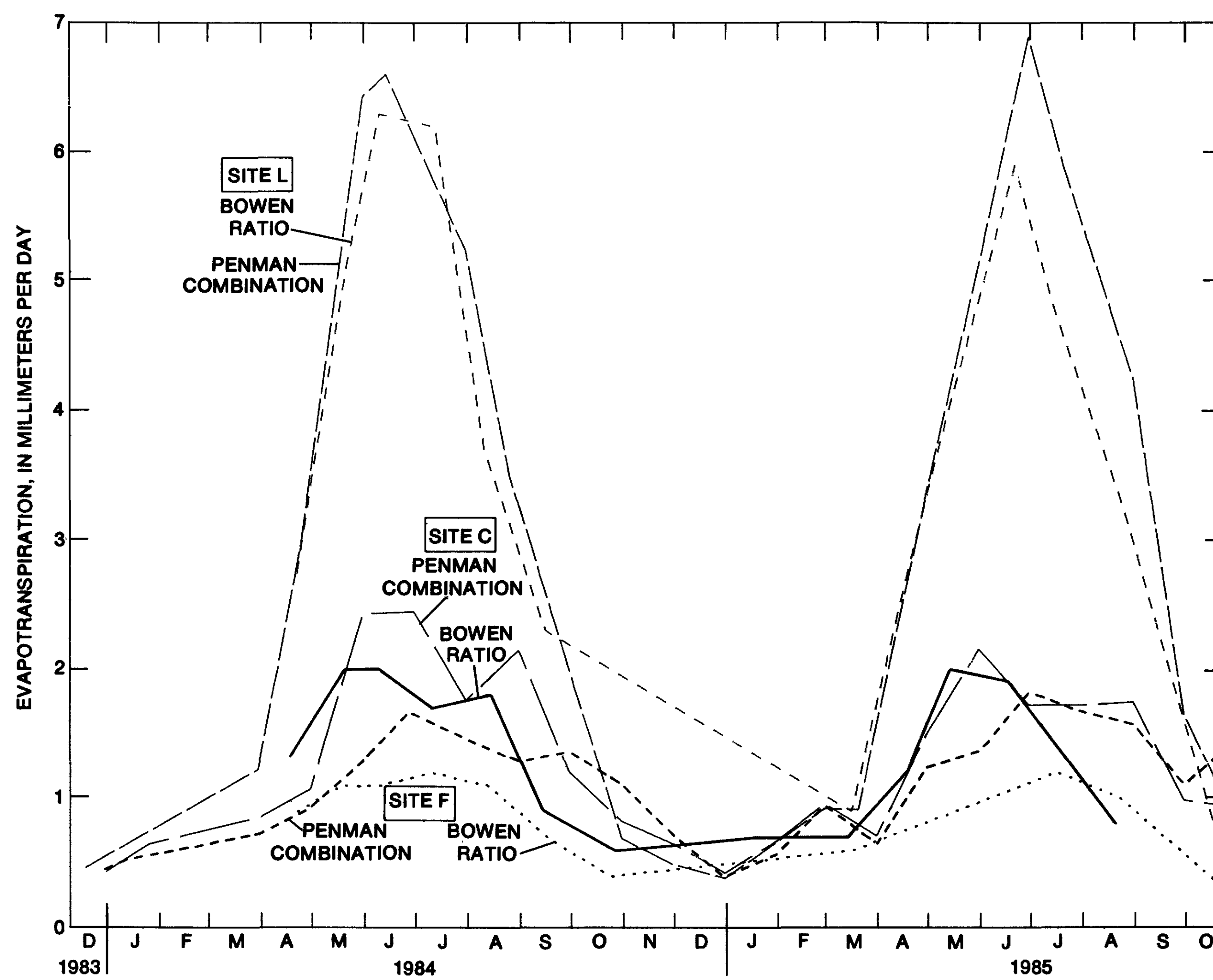


**Figure 24.** Comparison of monthly average evapotranspiration estimated by Bowen-ratio and Penman-combination methods at sites C, F, and L, December 1983–October 1985.

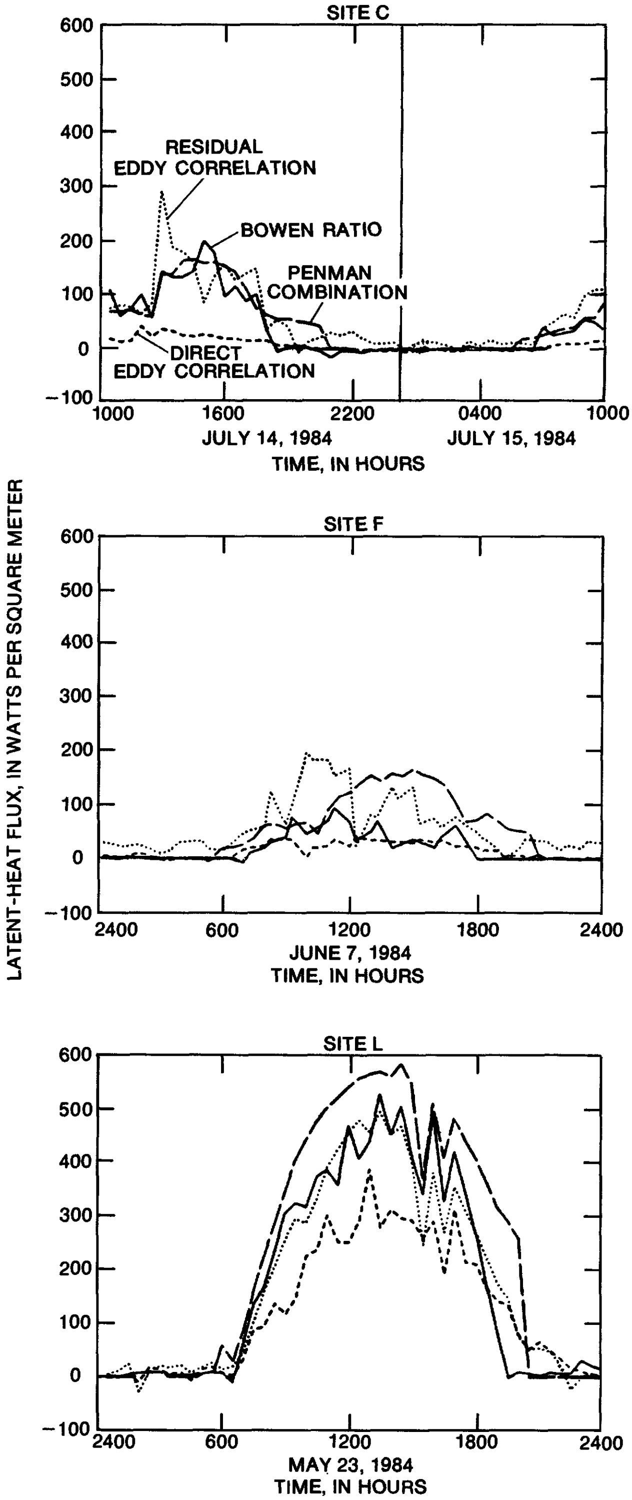


**Figure 25.** Comparison of one-half-hour latent-heat flux estimated by Bowen-ratio, direct and residual eddy-correlation, and Penman-combination methods at site C, July 14–15, 1984, site F, June 7, 1984, and site L, May 23, 1984.

## Comparison of Results With Those of Other Studies

The eddy-correlation instruments were tested by the author 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 with 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 W/m$^2$; daily estimates of latent-heat flux by the residual eddy-correlation method ranged from 243 to 260 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.

These *ET* estimates were mostly higher than the estimates in this study (table 5), except for the Penman-

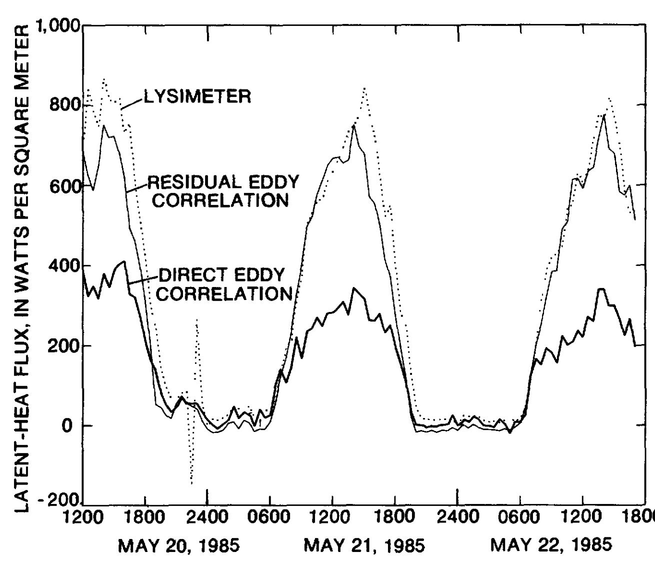


**Figure 26.** Comparison of one-half-hour latent-heat flux estimated by eddy-correlation method and a lysimeter at Phoenix, Arizona, May 20–22, 1985 (U.S. Department of Agriculture Water Conservation Laboratory, written commun., 1985; this study).

**Table 7.** Estimates of 1985 monthly evapotranspiration for California Irrigation Management Information System site by use of a floating lysimeter and 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 |

combination estimates at site L. The percent vegetation cover and available water at site L were similar to those values at the CIMIS site. The higher *ET* estimates by the Penman-combination method at site L for June and July compared with 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 with 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 (fig. 1). 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. Regression analysis of monthly average data indicates 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 indicate a low correlation with 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 were 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 energy was stored in the soil above the soil-heat-flux plate, and because 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 did 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, maintenance was minimal, and 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 from 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 varies 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 to 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 and 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 301 mm per year at a low-density scrub site to 1,137 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 with 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 in 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 represent an extensive data base of nearly 2 years' 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.** Daily average maximum and minimum and monthly mean meteorological data, and latent-heat-flux estimates by Penman-combination method, December 1983 through October 1985, at sites C, F, and L

[°C, degrees Celsius; g/m³, grams per cubic meter; m/s, meters per second; W/m², watts per square meter]

| Month | Air temperature (°C) | Vapor-density deficit (g/m³) | Vapor density (g/m³) | Windspeed (m/s) | Solar radiation (W/m²) | Net radiation (W/m²) | Soil-heat flux (W/m²) | Latent-heat flux (W/m²) |
|---|---|---|---|---|---|---|---|---|
| SITE C | | | | | | | | |
| *December 1983* | | | | | | | | |
| 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 |
| *January 1984* | | | | | | | | |
| 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 |
| *March 1984* | | | | | | | | |
| 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 |
| *April 1984* | | | | | | | | |
| 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 |
| *May 1984* | | | | | | | | |
| 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 |
| *June 1984* | | | | | | | | |
| 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 |
| *July 1984* | | | | | | | | |
| 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 |
| *August 1984* | | | | | | | | |
| 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 |
| *September 1984* | | | | | | | | |
| 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 |
| *October 1984* | | | | | | | | |
| 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 |
| *November 1984* | | | | | | | | |
| 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 |
| *December 1984* | | | | | | | | |
| 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 |

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

| Month | Air temperature (°C) | Vapor-density deficit ($g/m^3$) | Vapor density ($g/m^3$) | Windspeed (m/s) | Solar radiation ($W/m^2$) | Net radiation ($W/m^2$) | Soil-heat flux ($W/m^2$) | Latent-heat flux ($W/m^2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | SITE C--Continued | | | | |
| *January 1985* | | | | | | | | |
| 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 |
| *February 1985* | | | | | | | | |
| 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 |
| *March 1985* | | | | | | | | |
| 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 |
| *April 1985* | | | | | | | | |
| 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 |
| *May 1985* | | | | | | | | |
| 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 |
| *June 1985* | | | | | | | | |
| 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 |
| *July 1985* | | | | | | | | |
| 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 |
| *August 1985* | | | | | | | | |
| 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 |
| *September 1985* | | | | | | | | |
| 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 |
| *October 1985* | | | | | | | | |
| 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 mean meteorological data, and latent-heat-flux estimates by Penman-combination method, December 1983 through October 1985, at sites C, F, and L—*Continued*

| Month | Air temperature (°C) | Vapor-density deficit (g/m³) | Vapor density (g/m³) | Windspeed (m/s) | Solar radiation (W/m²) | Net radiation (W/m²) | Soil-heat flux (W/m²) | Latent-heat flux (W/m²) |
|---|---|---|---|---|---|---|---|---|
| | | | | SITE F | | | | |
| *December 1983* | | | | | | | | |
| Maximum | 8.4 | 4.0 | 6.6 | 3.9 | 113 | 51 | 12 | 22 |
| Minimum | .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 | -.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 |
| *August 1984* | | | | | | | | |
| 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 |
| *September 1984* | | | | | | | | |
| 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 |
| *October 1984* | | | | | | | | |
| 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 |
| *November 1984* | | | | | | | | |
| Maximum | 12.8 | 9.5 | 5.8 | 4.8 | 180 | 85 | 19 | 45 |
| Minimum | -.9 | .5 | 1.9 | 1.2 | 21 | 3 | -16 | 4 |
| Mean | 5.5 | 4.2 | 3.5 | 2.5 | 132 | 64 | 4 | 25 |
| *December 1984* | | | | | | | | |
| Maximum | 6.7 | 3.7 | 6.3 | 8.1 | 137 | 83 | 17 | 23 |
| Minimum | -9.7 | .3 | 1.6 | .8 | 29 | 9 | -18 | 4 |
| Mean | .0 | 1.5 | 3.8 | 2.1 | 102 | 46 | -1 | 13 |

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

| Month | Air temperature (°C) | Vapor-density deficit ($g/m^3$) | Vapor density ($g/m^3$) | Windspeed (m/s) | Solar radiation ($W/m^2$) | Net radiation ($W/m^2$) | Soil-heat flux ($W/m^2$) | Latent-heat flux ($W/m^2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | SITE F--Continued | | | | |
| *January 1985* | | | | | | | | |
| 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 |
| *February 1985* | | | | | | | | |
| 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 |
| *March 1985* | | | | | | | | |
| 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 |
| *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 mean meteorological data, and latent-heat-flux estimates by Penman-combination method, December 1983 through October 1985, at sites C, F, and L—*Continued*

| Month | Air temperature (°C) | Vapor-density deficit (g/m$^3$) | Vapor density (g/m$^3$) | Windspeed (m/s) | Solar radiation (W/m$^2$) | Net radiation (W/m$^2$) | Soil-heat flux (W/m$^2$) | Latent-heat flux (W/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | SITE L | | | | |
| *December 1983* | | | | | | | | |
| Maximum | 5.7 | 3.5 | 5.1 | 4.0 | 131 | 50 | 21 | 21 |
| Minimum | -.4 | 1.5 | 3.5 | 1.4 | 85 | 20 | 3 | 10 |
| Mean | 3.3 | 2.3 | 4.3 | 2.0 | 115 | 38 | 14 | 16 |
| *March 1984* | | | | | | | | |
| 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 |
| *April 1984* | | | | | | | | |
| 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 |
| *May 1984* | | | | | | | | |
| 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 |
| *June 1984* | | | | | | | | |
| 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 |
| *July 1984* | | | | | | | | |
| 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 |
| *August 1984* | | | | | | | | |
| 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 |
| *September 1984* | | | | | | | | |
| 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 |
| *October 1984* | | | | | | | | |
| 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 |
| *November 1984* | | | | | | | | |
| 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 |
| *December 1984* | | | | | | | | |
| Maximum | 4.4 | 3.9 | 5.2 | 8.7 | 140 | 69 | 3 | 24 |
| Minimum | -13.3 | .4 | 1.4 | .8 | 23 | -1 | -11 | 3 |
| Mean | -2.1 | 1.5 | 3.1 | 2.1 | 100 | 37 | -4 | 13 |

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

| Month | Air temperature (°C) | Vapor-density deficit (g/m³) | Vapor density (g/m³) | Windspeed (m/s) | Solar radiation (W/m²) | Net radiation (W/m²) | Soil-heat flux (W/m²) | Latent-heat flux (W/m²) |
|---|---|---|---|---|---|---|---|---|
| SITE L--Continued | | | | | | | | |
| *January 1985* | | | | | | | | |
| 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 |
| *February 1985* | | | | | | | | |
| 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 |
| *March 1985* | | | | | | | | |
| 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 |
| *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 |