Evapotranspiration for Three Sparse-Canopy Sites in the Black Rock Valley, Yakima County, Washington, March 1992 to October 1995

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CONVERSION FACTORS, VERTICAL DATUM, SYMBOLS, AND EQUATIONS

Multiply	By	To obtain
Area		
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
Density		
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot
Energy		
joule (J)	9.478×10^{-4}	British thermal unit
Energy-flux density		
watt per square meter (W/m^2)	5.285×10^{-3}	British thermal unit per square foot per minute
Energy and Mass		
joule per gram (J/g)	0.4298	British thermal unit per pound
Flow		
cubic meter per second	15,850	gallons per minute
Length		
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile

Multiply	By	To obtain
Mass		
gram (g)	2.205×10^{-3}	pound
Power		
watt (W)	3.4129	British thermal unit per hour
Pressure		
kilopascal (kPa)	0.1450	pound per square inch
Resistance		
second per meter (s/m)	0.3048	second per foot
Specific-heat capacity		
joule per gram per kelvin ([J/g]/K)	0.2388	British thermal unit per pound per degrees Fahrenheit
Temperature		
degrees Celsius (°C)	1.8°C + 32	degrees Fahrenheit
kelvin (K)	1.8 K - 459.67	degrees Fahrenheit
Velocity		
meter per second (m/s)	2.237	miles per hour
Volume		
cubic meter (m^3)	35.31	cubic foot

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.

SYMBOLS USED IN TEXT

β	Bowen ratio, unitless
C_p	Specific heat of air, equal to 1.005 joules per gram per degree Celsius
C_s	Specific heat of soil, in joules per kilogram per degree Celsius
C_w	Specific heat of water, in joules per kilogram per degree Celsius
D	Depth, in meters
d	Zero plane displacement height (distance from surface to mean height of heat, vapor, or momentum exchange), in meters
ET	Rate of evapotranspiration, in millimeters per day
e	Vapor pressure, in kilopascals
e_s	Saturated vapor pressure, in kilopascals
ε	Ratio of molecular weight of water to air, equal to 0.622

SYMBOLS USED IN TEXT--CONTINUED

$FX1$	Soil-heat flux measurement 1, in watts per square meter
$FX2$	Soil-heat flux measurement 2, in watts per square meter
G	Soil-heat flux, in watts per square meter
H	Sensible-heat flux, in watts per square meter
h	Canopy height, in meters
h_r	Relative humidity, in percent
K_h	Height-dependent exchange coefficient (eddy diffusivity) for heat transport, in square meters per second
K_w	Height-dependent exchange coefficient (eddy diffusivity) for water-vapor transport, in square meters per second
k	von Karman's constant, equal to 0.4, unitless
L	Latent heat of vaporization of water, in joules per gram
LE	Latent-heat flux, in watts per square meter
LE_p	Potential latent-heat flux, in watts per square meter
P	Atmospheric pressure, in kilopascals
ρ_a	Air density, in grams per cubic meter
ρ_b	Soil bulk density, in kilograms per cubic meter
$\mathfrak{R}$	Gas constant for dry air, equal to 0.28704 joules per gram per kelvin
R_n	Net radiation, in watts per square meter
r_c	Canopy resistance, in seconds per meter
r_h	Aerodynamic resistance to heat flow, in seconds per meter
r^2	Square of the correlation coefficient, unitless
S	Flux going into storage as soil heat, in watts per square meter
s	Slope of the saturation vapor-pressure curve at air temperature, in kilopascals per degree Celsius
T	Air temperature, in degrees Celsius
T_s	Soil temperature, in degrees Celsius
t	Time, in seconds
u	Wind speed, in meters per second
W	Percentage of water content by weight, in kilograms of water per kilogram of soil
z	Measurement height, in meters
z_h	Heat-transfer roughness length, in meters
z_m	Momentum roughness length, in meters
γ	Psychrometric constant, in kilopascals per degree Celsius

EQUATIONS USED IN TEXT

Number	Name and source or derivation	Equation
1.	Energy budget (Brutsaert, 1982, p. 2)	$R_n = LE + H + G$
2.	Latent-heat of vaporization of water (W.D. Nichols, U.S. Geological Survey, written commun., 1990)	$L = \frac{\Re[6,788.6 - 5.0016(T + 273.15)]}{\varepsilon}$
3.	Latent-heat of vaporization of water (Reduction of eq. 2)	$L = 2,502.3 - 2.308\ T$
4.	Soil-heat flux (Campbell Scientific, Inc., 1991, sec. 4, p. 3)	$G = \left(\frac{FX1 + FX2}{2}\right) + S$
5.	Soil-heat storage (Campbell Scientific, Inc., 1991, sec. 4, p. 3)	$S = \left(\frac{\Delta T_s}{\Delta t}\right) D\ \rho_b\ [C_s + (W\ C_w)]$
6.	Bowen ratio (Bowen, 1926)	$\beta = \frac{H}{LE}$
7.	Bowen ratio (Rosenberg and others, 1983, p. 255)	$\beta = \frac{P\ C_p\ K_h \frac{dT}{dz}}{L\ \varepsilon\ K_w \frac{de}{dz}}$
8.	Bowen ratio (Tanner, 1988)	$\beta = \frac{P\ C_p\ \Delta T}{L\ \varepsilon\ \Delta e}$
9.	Psychrometric constant (Rosenberg and others, 1983, p. 255)	$\gamma = \frac{P\ C_p}{L\ \varepsilon}$

EQUATIONS USED IN TEXT--CONTINUED

Number	Name and source or derivation	Equation
10.	Bowen ratio (Substitution of eq. 9 into eq. 8)	$\beta = \gamma \frac{\Delta T}{\Delta e}$
11.	Sensible-heat flux (Rearrangement of eq. 6)	$H = \beta\ LE$
12.	Latent-heat flux (Substitution of eq. 11 for H, then rearrangement of eq. 1)	$LE = \frac{R_n - G}{1 + \beta}$
13a.	Rate of evapotranspiration (Campbell, 1977, p. 141)	$\mathrm{ET} = 86.4 \frac{LE}{L}$
13b.	Latent-heat flux (Rearrangement of equation 13a)	$LE = \frac{ET\ L}{86.4}$
14.	Vapor pressure (Rearrangement of equation for h_r in Rosenberg and others, 1983, p. 171)	$e = 0.01\ e_s\ h_r$
15.	Saturated vapor pressure (Stull, 1988, p. 276; equation adjusted for °C)	$e_s = 0.6112\ exp\left[\frac{17.67\ T}{T + 243.5}\right]$
16.	Slope of the saturated vapor pressure curve (Derivation of eq. 15 and conversion of T in K to °C)	$s = 0.6112\left[\left(\frac{17.67}{T + 243.5} - \frac{17.67\ T}{(T + 243.5)^2}\right) exp\left(\frac{17.67\ T}{T + 243.5}\right)\right]$

Number	Name and source or derivation	Equation
17.	Aerodynamic resistance to heat (neutral conditions) (Campbell, 1977, p. 138)	$r_h = \dfrac{ln\left[\dfrac{z-d+z_h}{z_h}\right] ln\left[\dfrac{z-d+z_m}{z_m}\right]}{k^2 u}$
18.	Penman equation (potential evapotranspiration) (Monteith, 1965)	$LE_p = \dfrac{s(R_n - G) + \rho_a C_p (e_s - e)/r_h}{s + \gamma}$
19.	Penman-Monteith equation (Monteith, 1965)	$LE = \left[\dfrac{s\left[R_n - G\right] + \left[\rho_a C_p (e_s - e)\right]/r_h}{s + \gamma\left[(r_c + r_h)/r_h\right]}\right]$
20.	Canopy resistance (Rearrangement of eq. 19)	$r_c = \dfrac{r_h}{\gamma}\left(\dfrac{1}{LE}\left[s(R_n - G) + \left\{\dfrac{\rho_a C_p (e_s - e)}{r_h}\right\}\right] - s\right) - r_h$

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ABSTRACT

This report evaluates evapotranspiration estimated with the Bowen-ratio and Penman-Monteith methods for three sparse-canopy sites in an area known as the Big Flat in the Black Rock Valley of Yakima County, Washington. These sites are located in sagebrush (Black Rock Valley and Firewater Canyon sites) and grassland (Bird Canyon site). Bowen-ratio data were collected with a cooled-mirror hygrometer system (Bowen-ratio instruments) for various periods from March 1992 to October 1995. Additional Bowen-ratio data were collected using sensors at fixed-heights (fixed-sensor instruments) for various periods from April 1993 to October 1995. Penman-Monteith data were collected from May 1992 to March 1993. Generally, latent-heat flux and evapotranspiration estimated with Penman-Monteith and fixed-sensor instruments agreed closely with latent-heat flux and evapotranspiration estimated with Bowen-ratio instruments. However, these comparisons were sometimes poor during periods of high wind at night and during very dry periods in summer and fall.

Evapotranspiration estimates at the three sites showed similar seasonal trends, but daily and cumulative evapotranspiration estimates differed considerably, even though the sites were located within 3.5 kilometers of each other. Daily evapotranspiration ranged from less than 1 millimeter during dry periods in late summer, fall, and winter, to over 4 millimeters during periods of peak plant growth in spring. From October 1994 to September 1995, cumulative precipitation at all three sites differed by only 4 percent, but the Black Rock Valley and Bird Canyon sites showed about 30 percent more cumulative evapotranspiration than the Firewater Canyon site. For October 1994 to September 1995, cumulative evapotranspiration at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites was, respectively, 139 percent, 136 percent, and 97.2 percent of cumulative precipitation. For annual periods from 1992 to 1995 at the Black Rock Valley site, cumulative evapotranspiration ranged from 133 to 175 percent of cumulative precipitation.

The results of this study suggest that annual precipitation and evapotranspiration are nearly equal for the Firewater Canyon site (as they are for sites on the Arid Lands Ecology Reserve, about 40 kilometers away, but that surface runoff or ground water from upslope areas may provide additional water for evapotranspiration at the Black Rock Valley and Bird Canyon sites. Because the hydrogeology of the Big Flat in the Black Rock Valley is not well known, additional studies in this area would be needed to confirm that hypothesis.

INTRODUCTION

Most of the precipitation that falls in semiarid areas of eastern Washington is returned to the atmosphere as evapotranspiration (ET). ET, the amount of water evaporated from soil and other surfaces plus the amount of water transpired by plants, thus plays an important part in the hydrologic cycle for eastern Washington. Combined with precipitation and surface-water discharge data, ET estimates are commonly used to estimate ground-water recharge (Gee and Kirkham, 1984; Gee and Hillel, 1988; Bauer and Vaccaro, 1990). Thus, ET estimates are important to resource managers.

ET is one of the most difficult components of the hydrologic cycle to quantify because of the complexity of collecting the data needed for its computation. Many environmental factors contribute to ET, each of which requires accurate measurement of a number of variables under different conditions. Some of these factors are particularly difficult to measure in semiarid areas; for example, the extremes of temperature and relative humidity are occasionally beyond the data-collection capabilities of the Bowen-ratio instruments.

Background

In order to better estimate ET in eastern Washington, an ET project was established in August 1989 by the U.S. Geological Survey and the State of Washington, Department of Ecology. These projects were continued in 1990, 1991, 1992, and 1993 to form a series of four projects and five reports. The objectives of these projects were to make long-term measurements of ET for several sites in eastern Washington and to investigate a method of estimating ET requiring only standard meteorological or easily collected data.

The results of these projects are documented in this and four previous reports. The first of these reports describes ET methods and preliminary results for a grassland in Snively Basin (Snively Basin site) of the Arid Lands Ecology (ALE) Reserve, Benton County, from May to October 1990 (Tomlinson, 1994). The second report describes ET at the Snively Basin site from May 1990 to September 1991 and for meadow and marsh sites on the Turnbull National Wildlife Refuge (Turnbull meadow and Turnbull marsh sites) near Spokane from May to September 1991 (Tomlinson, 1995). The third report describes ET from six sites in eastern Washington—the Snively Basin site, Turnbull meadow site, Turnbull marsh site, Black Rock Valley site, and two sparse-canopy sites on the ALE Reserve (grass lysimeter site and sage lysimeter site)—from 1990 to 1992 (Tomlinson, 1996a). The fourth report compares the Bowen-ratio and eddy-correlation methods with weighing lysimeters at the grass and sage lysimeter sites on the ALE Reserve in 1993 and 1994 (Tomlinson, 1996b)

Purpose and Scope

This report describes ET for three sparse-canopy sites in an area locally called the Big Flat in an unnamed valley of the Black Rock Valley near Moxee City, Yakima County, Washington (figs. 1 and 2). The Bowen-ratio and Penman-Monteith methods were used to estimate ET at these sites. The purposes of this part of the series of ET projects were to (1) estimate long-term ET for a relatively remote, undocumented area, (2) investigate a method of estimating ET using standard meteorological or easily collected data, and (3) develop a water budget using ET and precipitation estimates.

Acknowledgments

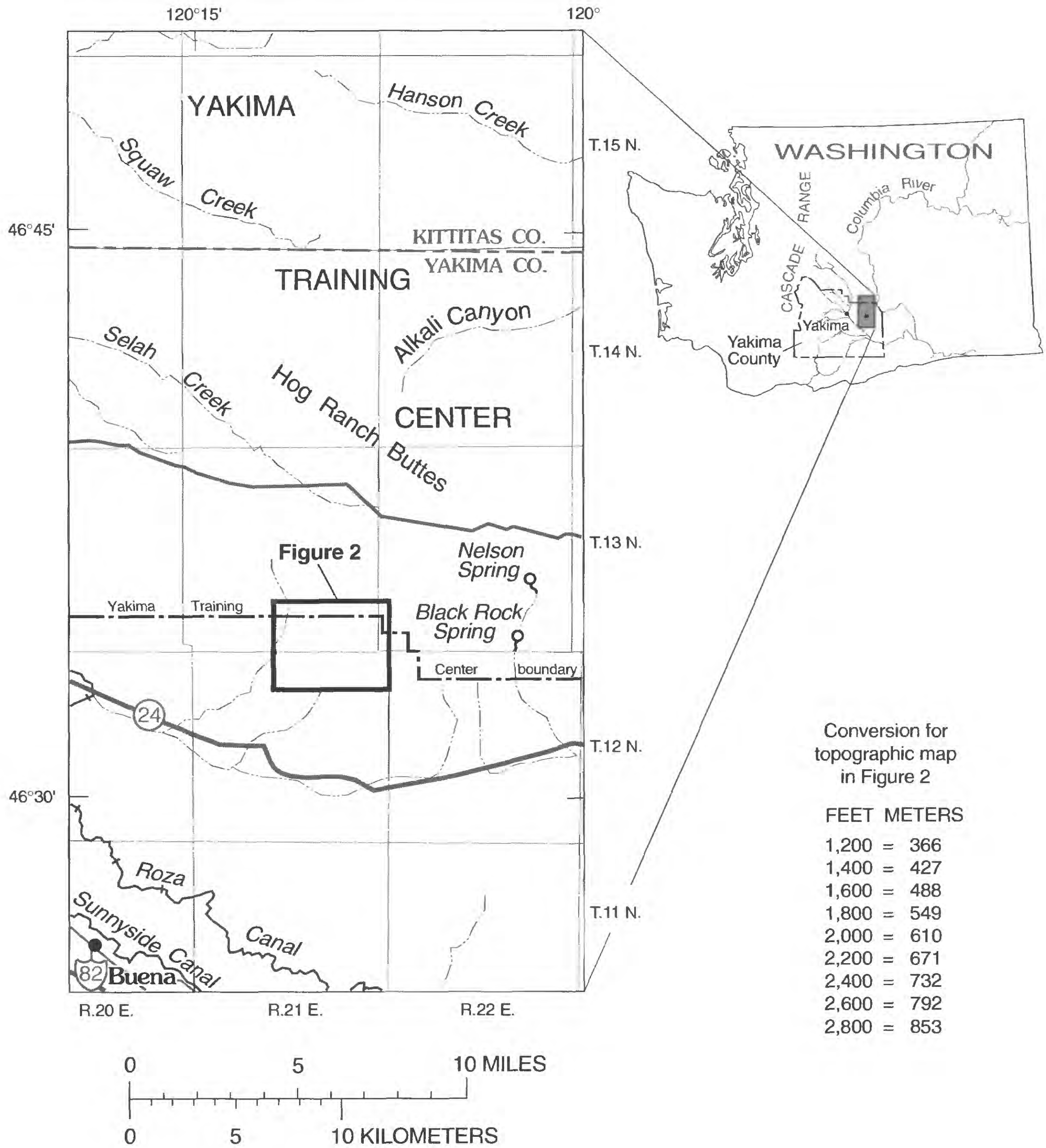
The author thanks Mr. Simon Martinez, Mr. Mike Martinez, and their families for their cooperation and permission to install ET instruments on their property and to access the sites using roads on their property. Also, thanks are given to the U.S. Army, Department of Defense, for their permission to access the sites using roads on the Yakima Training Center.

DESCRIPTION OF THE STUDY SITES

The study sites are located within about 3.5 kilometers (km) of each other in semiarid sparse-canopy native sagebrush and naturalized (exotic species that have become established as if native) grassland vegetation about 14 km east-northeast of Moxee City, Wash. (figs. 1 and 2). The sites are situated on private property just south of the border with the Yakima Training (Firing) Center. The main site (Black Rock Valley site), established in March 1992, lies at an altitude of 762 meters (m) in an area of sagebrush 2.5 km south from the crest of the Yakima Ridge and 1.3 km north of a smaller, unnamed ridge (fig 2). Another site (Bird Canyon site), established in October 1994, is at an altitude of 735 m in a field of naturalized wheat and crested wheat grass about 0.8 km west of the Black Rock Valley site (fig. 2). The third site (Firewater Canyon site) is at 768 m in an area of sagebrush about 2.5 km east of the Black Rock Valley site (fig 2). Altitudes in the area range from 1,278 m at the crest of the Yakima Ridge to 700 m at the lowest part of the unnamed valley.

Climate

The semiarid climate of eastern Washington results primarily from the rain-shadow effect of the Cascade Range (fig. 1). The Cascade crest varies between 1,200 and 3,050 m above sea level and forms an effective barrier to storms moving in from the Pacific Ocean. West of the Cascades, Olympia receives 1,270 millimeters (mm) of precipitation annually, while east of the Cascades, Yakima receives only 203 mm a year (Ruffner and Bair, 1987). From Yakima, precipitation gradually increases to the east where Walla Walla receives 383 mm and Spokane receives 411 mm annually (Ruffner and Bair, 1987).



Conversion for topographic map in Figure 2

FEET		METERS
1,200	=	366
1,400	=	427
1,600	=	488
1,800	=	549
2,000	=	610
2,200	=	671
2,400	=	732
2,600	=	792
2,800	=	853

Figure 1.--Location of study area.

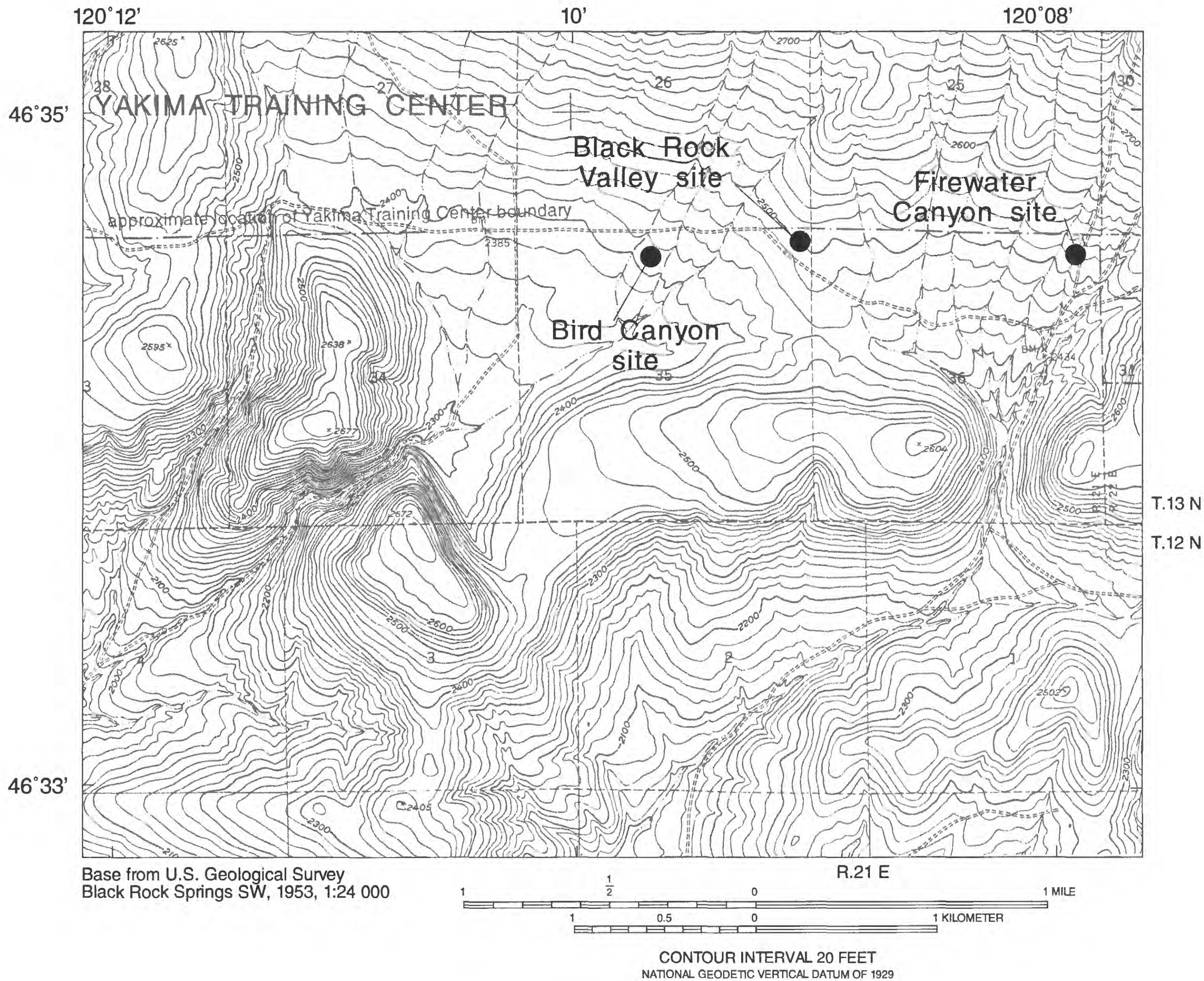


Figure 2.--Location of Black Rock Valley, Bird Canyon, and Firewater Canyon sites.

Prior to this project, no precipitation data were collected in the Black Rock Valley because of its remote location. The 735-768 m altitude of the study sites suggest that their average precipitation should be slightly greater than that at Moxee City (472 m altitude), which averages 198 mm annually (National Oceanic and Atmospheric Administration, 1994). However, from May 1992 to June 1995, total precipitation at Moxee City (National Oceanic and Atmospheric Administration, 1992, 1993, 1994, 1995) was 2 percent more than total precipitation measured by a tipping-bucket gage at the Black Rock Valley site. Precipitation patterns in the Black Rock Valley are similar to those at the ALE Reserve, about 40 km to the southeast. At the ALE Reserve, about 75 percent of the annual precipitation falls from October to April, about one-fourth of it as snow (Stone and others, 1983). June to September is the driest time of year, though convective storms during this period can bring as much as 20 percent of the annual precipitation.

Dew is of minor significance and adds only small amounts of water to the annual precipitation at the study sites. No measurements of dew have been made in the Black Rock Valley, but on the ALE Reserve, Rickard and others (1988) estimated dew at less than 5 percent of the annual precipitation on the basis of available meteorological data. Monteith (1963a) estimated that water input from dewfall can range from 10 to 40 mm in some climates.

Air temperatures at the study sites are primarily continental (influenced more by air masses moving over land rather than over water), but frequent storm fronts move in from the Pacific Ocean, mainly during the winter months, moderating temperatures and bringing precipitation. At Moxee City, about 14 km from the Black Rock Valley site, the average annual air temperature is 9.2 degrees Celsius (^{o}C) (National Oceanic and Atmospheric Administration, 1994). Air temperature extremes at Moxee City for the period 1948 to 1995 range from -31 to 42^{o}C (J. Ashby, Western Regional Climate Center, oral commun., 1996).

Vegetation

Vegetation at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites consists primarily of sagebrush and grasses. At the Black Rock Valley and Firewater Canyon sites, vegetation is typical of native plants found growing over a large part of the Columbia Plateau—big sagebrush (*Artemesia tridentata*), bluebunch wheatgrass (*Agropyron spicatum*), and Sandberg's bluegrass (*Poa sandbergii*) predominate. Stiff sagebrush (*Artemesia rigida*) and desert buckwheat (*Eriogonum thymoides*) also grow at the Black Rock Valley site, but relatively few other plants grow near the site—there is a noticeable absence of non-grass annuals and perennials. At the Black Rock Valley site, grasses average 0.4 m in height and sagebrush 0.9 m in height; plants cover 10 to 40 percent of the soil surface. At the Black Rock Valley site, sagebrush-covered areas extend over 3 km to the northwest, north, and east. Toward the south and southwest, however, sagebrush extends only about 400 m, where a field of naturalized grasses begins. The Bird Canyon site is located in this field.

The Bird Canyon site is located in an abandoned field of naturalized grasses. Vegetation consists primarily of wheat (*Triticum aestivum*), crested wheat grass (*Agropyron cristatum*), and cheatgrass (*Bromus tectorum*). Crested wheatgrass is a forage plant introduced from Europe and Asia, and cheatgrass is an invasive grass introduced to Washington from Europe about 1890 (Franklin and Dyrness, 1988). Plants cover 75 to 90 percent of the surface and average 0.5 to 0.8 m high in fall, winter, and spring, and 1.0 m high in summer. The field extends about 1.3 km west, 0.7 km south, 0.4 km east, and 0.3 km north of the Bird Canyon site (fig. 2).

At the Firewater Canyon site, the grasses and sagebrush are denser and slightly higher than at the Black Rock Valley site. Grasses average 0.5 m and sagebrush 1.0 m in height and plants cover 30 to 70 percent of the surface. Many annuals and perennials also grow, such as showy phlox (*Phlox speciosa*) and lupine (*Lupinus* sp.). Similar vegetation extends for at least 2 km in all directions from the Firewater Canyon site.

At all of the study sites, vegetation grows most rapidly during the wet winter and spring seasons. Plant roots grow during the winter and spring. Above-ground plant growth usually peaks from early April to mid-June, when ET is also at its maximum because of the transpiration from the growing vegetation. Beginning in June, dryer weather causes the grasses to go to seed and become dormant by July or August. At this time, sagebrush begins to lose a number of leaves in response to the drying conditions. In late summer and early fall, usually the driest time of year, sagebrush blooms while the grasses are completely dormant. Grasses begin growing in fall after the first major precipitation.

Geology and Soils

The study sites are located in the Columbia Plateau physiographic province. The major surficial rock features of this area are numerous layers of basalt, the result of lava flows during the Miocene and Pliocene epochs, with thin sedimentary and volcanic ash interbeds. Silt, gravel, sand other alluvial deposits left as a result of the so-called Spokane Flood (actually a series of floods) that swept across the Columbia Plateau during the Pleistocene epoch (Alt and Hyndman, 1984) cover much of the lower altitudes of the Columbia Plateau. Wind-blown loess was deposited over much of the Plateau during the Pleistocene and Holocene epochs. Bedrock is basalt.

The soils found at the study sites are silt loams as described by the U.S. Department of Agriculture (1985). Willis silt loam exists at the Black Rock Valley and Bird Canyon sites. It is a moderately deep, well-drained soil formed on uplands from loess. Permeability of the Willis silt loam is low to moderate, water-holding capacity is high, and runoff potential is moderate. A hardpan exists in Willis silt loam at a depth of 0.5 to 1.0 m. Ritzville silt loam, also formed from loess, is found at the Firewater Canyon site. This soil occurs on uplands and is very deep and well-drained. Permeability of the Ritzville silt loam is moderate, water-holding capacity is high, and runoff potential is moderate. Bulk densities of soil samples collected at the Bird Canyon, Black Rock Valley, and Firewater Canyon sites by the USGS during the study ranged from 1,400 to 1,800 kilograms per cubic meter (kg/m^3). Average soil bulk density was about 1,500 kg/m^3 at each site.

Hydrology

The study sites in the Black Rock Valley are located at the base of an alluvial fan on the south side of the Yakima Ridge (fig. 2). The alluvial fan contains several shallow ephemeral channels in the vicinity of the study sites. Water flows in these channels, which in most cases are incised less than 0.5 m below the surrounding soil surface, only after intense rainfalls. South of the study sites, these channels merge into two larger and deeper channels that funnel through two canyons. Vegetation in these canyons is denser and more lush than in surrounding areas—several small cottonwood (*Populus nigra*) and willow (*Salix* sp.) trees grow in the channel about 1.5 km south of the Firewater Canyon site indicating the presence of water. Depths to ground water are not known at the Black Rock Valley or Firewater Canyon sites. However, water was first found at about 150 to 200 m below the land surface while drilling a well in the field in which the Bird Canyon site is located (S. Martinez, oral commun., 1994).

METHODS OF ESTIMATING EVAPOTRANSPIRATION

The Bowen-ratio and Penman-Monteith methods were used to estimate ET in this study. Both methods require instruments to collect data for a number of variables to estimate ET. The Bowen-ratio method requires data for net radiation, air temperature and vapor pressure at two heights, soil temperature, and soil-heat flux. The Penman-Monteith method requires measurement of net radiation, soil-heat flux, air temperature, relative humidity, and wind speed, along with estimates of canopy resistance. Field personnel collected soil samples during each site visit to determine soil-water content and bulk density.

In this study, data for estimating ET with the Bowen-ratio method was collected with two instrument systems. In the first system, air temperature was measured with fine-wire thermocouples and vapor pressure was estimated with air from two heights routed to a cooled-mirror hygrometer minimizing (fine-wire thermocouples) or eliminating (cooled-mirror hygrometer) sensor bias. In this report, the fine-wire thermocouple/cooled-mirror hygrometer system is referred to as the Bowen-ratio system, or Bowen-ratio instruments. In the second system, air temperature and vapor pressure were determined from two air-temperature/relative humidity probes set at two fixed heights—thus sensor bias was not accounted for. In this report, the setup using sensors at fixed heights is termed the fixed-sensor system, or fixed-sensor instruments. Though the instruments are different in the Bowen-ratio and fixed-sensor systems, both collect data to estimate ET with the Bowen-ratio method—the method is the same, but the instruments are different. The fixed-sensor system allowed the Bowen-ratio method to be used in winter, when the Bowen-ratio system of instruments could not be operated because of the cooled-mirror hygrometer's sensitivity to below-freezing air temperatures. The fixed-sensor system also allowed Bowen-ratio ET estimates to be made when fine-wire thermocouples broke or the cooled-mirror hygrometer failed or provided unreasonable vapor-pressure gradients during the spring, summer, and fall. The Bowen-ratio and fixed-sensor systems were used at all three sites. The Penman-Monteith setup was used only at the Black Rock Valley site.

Instruments collected data for the methods used in this study for different time periods at each site (fig. 3). At the Black Rock Valley site, Bowen-ratio instruments collected data from March to October 1992, April to October 1993, March to November 1994, and March to October 1995, and Penman-Monteith instruments collected data from May 1992 to March 1993 and fixed-sensor instruments collected data from April 1993 to October 1995. At the Bird Canyon and Firewater Canyon sites, Bowen-ratio instruments collected data from October to November 1994 and from March to October 1995 while fixed-sensor instruments collected data from October 1994 to October 1995.

Instrumentation

Figure 4 shows the instruments used to collect data needed to estimate ET at the Black Rock Valley (fig. 4a), Bird Canyon (fig. 4b), and Firewater Canyon (fig. 4c) sites, and table 1 describes each of them. Bowen-ratio, fixed-sensor, and Penman-Monteith instruments were used at the study sites (fig. 4). More detailed information on the instruments is presented by Tomlinson (1994, p. 6-11). Instruments collected data at 1- to 10-second intervals and data loggers averaged collected data at 20-minute intervals during spring, summer, and early fall, and at 60-minute intervals during the winter.

The Bowen-ratio systems were composed of several delicate instruments requiring regular maintenance and careful calibration to maintain accuracy. Bowen-ratio systems consisted of two fine-wire thermocouples (to measure air temperature at two heights), two vapor-pressure intakes connected to one cooled-mirror hygrometer (to measure vapor pressure at the same two heights as air temperature), a net radiometer, one set of four averaging soil-temperature thermocouples, and two soil-heat flux transducers. The fine-wire thermocouples and air intakes were located on instrument arms that were about 0.7 m above the canopy for the lower arm and 3.0 m above the canopy for the upper arm. The fineness of the thermocouple wires minimized solar heating of the thermocouples, so sensor bias was minimized. The air from the two intakes was routed alternately at two-minute intervals to one cooled-mirror. Using one cooled mirror eliminated sensor bias that could result if two independent instruments were used. Because of suspected leaks in the Bowen-ratio system at the Black Rock Valley site in April and early May 1993, erroneous vapor-pressure gradients resulted—the problem was hard to detect because the Bowen-ratio system provided reasonable vapor-pressure values, but erroneous vapor-pressure gradients. This problem provided the impetus for trying the fixed-sensor system as a check on the Bowen-ratio system vapor-pressure gradients. Other Bowen-ratio system problems occurred, primarily with the cooled-mirror hygrometer, on numerous occasions throughout the study period at all sites. These problems included icing of the cooled-mirror during freezing or near-freezing weather, inexplicable loss of calibration of the cooled-mirror, failure or erratic operation of the pump for the cooled mirror, and damage to fine-wire thermocouples, net radiometers, and soil-heat flux transducers caused by birds and mammals.

Because of several inexplicable problems with the cooled-mirror hygrometer in September and October 1992, system leaks in April and May 1993, and the inability to operate the cooled-mirror hygrometer during winter due to its sensitivity to freezing temperatures, a fixed- sensor system was set up at the Black Rock Valley site in April 1993. This fixed-sensor system utilized the Bowen-ratio method except that sensor bias was not eliminated—the air-temperature and relative-humidity sensors (which were used to calculate vapor pressure) were not interchanged. Campbell Scientific CR-207 temperature-relative humidity probes (table 1, fig. 4) were used for the fixed-sensor system. These probes were set at the same heights above the canopy as the Bowen-ratio arms, 0.7 m and 3.0 m for the lower and upper probes, respectively. Under many conditions, such as cool air temperatures (below 25°C), windy conditions (wind speeds greater than about 3 meters per second (m/s)), and rainy periods, air-temperature and vapor-pressure data from the Bowen-ratio systems compared very favorably with data from the fixed-sensor systems. These favorable comparisons allowed Bowen-ratio ET estimates to be made using the fixed-sensor systems during winter and during periods when the cooled-mirror hygrometers were not operating properly.

The Penman-Monteith system consisted of one air-temperature relative-humidity probe, a net radiometer, two soil-heat flux transducers, a set of four averaging soil-temperature thermocouples, and an anemometer. The anemometer was set 3.0 m above the canopy. Additional data collected by the Penman-Monteith systems but not required for the Penman-Monteith method were solar radiation (by a pyranometer) and precipitation (by a tipping-bucket gage). Also, two precipitation storage gages were installed at each site from October 1994 to October 1995.

BLACK ROCK VALLEY SITE

INSTRUMENTS	Year	January	February	March	April	May	June	July	August	September	October	November	December
Bowen ratio	1992			●	●	●	●	●	●	●	●		
Penman-Monteith	1992					●	●	●	●	●	●	●	●
Fixed sensor	1992												
Bowen ratio	1993				●	●	●	●	●	●	●		
Penman-Monteith	1993	●	●	●									
Fixed sensor	1993				●	●	●	●	●	●	●	●	●
Bowen ratio	1994			●	●	●	●	●	●	●	●	●	
Penman-Monteith	1994												
Fixed sensor	1994	●	●	●	●	●	●	●	●	●	●	●	●
Bowen ratio	1995			●	●	●	●	●	●	●	●		
Penman-Monteith	1995												
Fixed sensor	1995	●	●	●	●	●	●	●	●	●	●		

BIRD CANYON SITE

INSTRUMENTS	Year	January	February	March	April	May	June	July	August	September	October	November	December
Bowen ratio	1992												
Fixed sensor	1992												
Bowen ratio	1993												
Fixed sensor	1993												
Bowen ratio	1994											●	
Fixed sensor	1994										●	●	●
Bowen ratio	1995			●	●	●	●	●	●	●	●		
Fixed sensor	1995	●	●	●	●	●	●	●	●	●	●		

FIREWATER CANYON SITE

INSTRUMENTS	Year	January	February	March	April	May	June	July	August	September	October	November	December
Bowen ratio	1992												
Fixed sensor	1992												
Bowen ratio	1993												
Fixed sensor	1993												
Bowen ratio	1994										●	●	
Fixed sensor	1994										●	●	●
Bowen ratio	1995			●	●	●	●	●	●	●	●		
Fixed sensor	1995	●	●	●	●	●	●	●	●	●	●		

Figure 3.--Instruments used to collect evapotranspiration data and periods of data collection at the study sites.

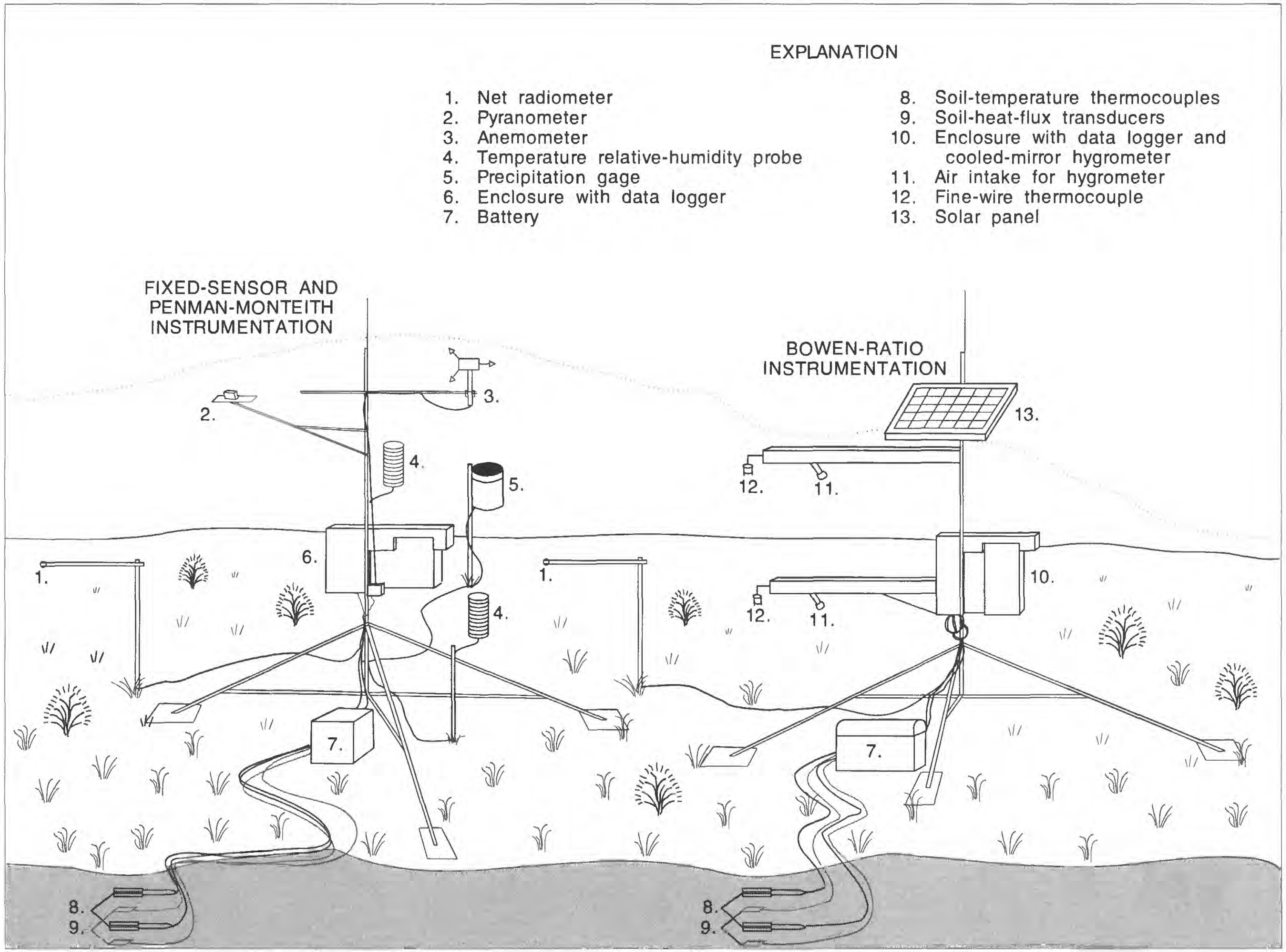


Figure 4.--Evapotranspiration instrument setups.

For the Bowen-ratio and Penman-Monteith methods, averages of Bowen-ratio, fixed-sensor, and Penman-Monteith system net radiometers, soil-heat flux transducers, and soil-temperature thermocouples were used to provide a single value for net radiation and soil-heat flux at each site. At the Black Rock Valley site, two net radiometers (three from August 1994 to October 1995), four soil-heat flux transducers (six from August 1994 to October 1995), and two sets of four averaging soil-temperature thermocouples (three sets from August 1994 to October 1995) were used. At the Bird Canyon and Firewater Canyon sites, two net radiometers, four soil-heat flux transducers, and two sets of four averaging soil-temperature thermocouples were used. This setup reduced the chance of using aberrant net radiation and soil-heat flux values that were not representative of the overall site conditions; it also allowed direct comparison of the different methods used to estimate ET at each site. Average differences in net radiometer measurements at each site were small, about 4 percent. Soil-heat-flux measurements at each site were more variable, about 30 percent, and these differences may produce a 10 percent change in daily ET, within the 12 percent error possibly introduced by the instruments themselves (Tomlinson, 1995, p. 14-15).

Figure 4a.--Fixed-sensor (left) and Bowen-ratio (right) instruments at the Black Rock Valley site, August 20, 1993.

Figure 4b.--Fixed-sensor (left) and Bowen-ratio (right) instruments at the Bird Canyon site, November 2, 1994.

Figure 4c.--Fixed-sensor (left) and Bowen-ratio (right) instruments at the Firewater Canyon site, November 2, 1994.

Table 1.--*Instrumentation used at evapotranspiration study sites*

Instrument type	Function	Manufacturer (Model)
Data logger	Scan instruments, record and process data	Campbell Scientific (21X)
Net radiometer	Measure net radiation	Radiation and Energy Balance Systems (Q-6)
Pyranometer	Measure solar and diffuse radiation	LI-COR (LI-200S)
Anemometer	Measure wind speed	Met One (014A)
Temperature-relative humidity probe	Measure air temperature and relative humidity	Campbell Scientific (CR-207)
Rain gage	Measure rainfall	Texas Electronics (TE-525)
Soil-temperature thermocouple	Measure average soil temperature	Radiation and Energy Balance Systems (TCAV)
Soil-heat flux transducer	Measure soil-heat flux	Radiation and Energy Balance Systems (HFT-1)
Cooled-mirror hygrometer	Measure vapor pressure and dew point	General Eastern (DEW-10) and Campbell Scientific (023)
Air-temperature thermocouple	Measure air temperature	Campbell Scientific (FWTC-1, FWTC-3, CA-127)

Energy Budgets

Energy-budget methods, such as the Bowen-ratio and Penman-Monteith methods, use the terms, symbols, and equations outlined at the beginning of the report. Detailed information on the Bowen-ratio and Penman-Monteith methods is presented by Tomlinson (1994, p. 11-17). Additionally, the Bowen-ratio and Penman-Monteith methods are described in great detail in textbooks written by Campbell (1977), Brutsaert (1982), Rosenberg and others (1983), and Monteith and Unsworth (1990). The notation and form of the equations used in these texts may differ from those used in this report, but the principles are the same.

ET involves a phase change of water from liquid to vapor (a process requiring energy) and the movement of that vapor into the atmosphere. ET can be conceptualized by an energy budget at each of the three study sites. This energy budget has four major flux components: net radiation, latent-heat flux, sensible-heat flux, and soil-heat flux. Field measurement of the energy-budget components encompasses a layer with an upper boundary just above the plant canopy and a lower boundary just below the soil surface (fig. 5), called the canopy layer in this report. In the energy-budget equation (eq. 1), net radiation equals the sum of the other three fluxes.

Net radiation, R_n, defined as the sum of all incoming shortwave solar radiation and incoming longwave sky radiation minus the sum of reflected solar radiation and outgoing longwave radiation (Haan and others, 1982), provides the major energy source for the energy budget. Net radiation is considered positive when the sum of the incoming radiation fluxes exceeds the sum of the outgoing radiation fluxes.

Latent-heat flux, LE (eq. 13b), results from the vaporization and movement of water. It is the product of the latent-heat of vaporization of water (eqs. 2, 3) and ET (eq. 13a). In this report, latent-heat flux is considered positive when vapor is transferred upward across the canopy layer.

Sensible-heat flux, H (eq. 11), is a turbulent, temperature-gradient driven heat flux resulting from differences in temperature between the soil and vegetative surfaces and the atmosphere. In this report, sensible-heat flux is considered positive when heat is transferred upward from the surface across the upper boundary of the canopy layer. During the daytime, positive sensible-heat flux is often the result of surface heating. At night, sensible-heat flux is often less than zero, the result of surface cooling.

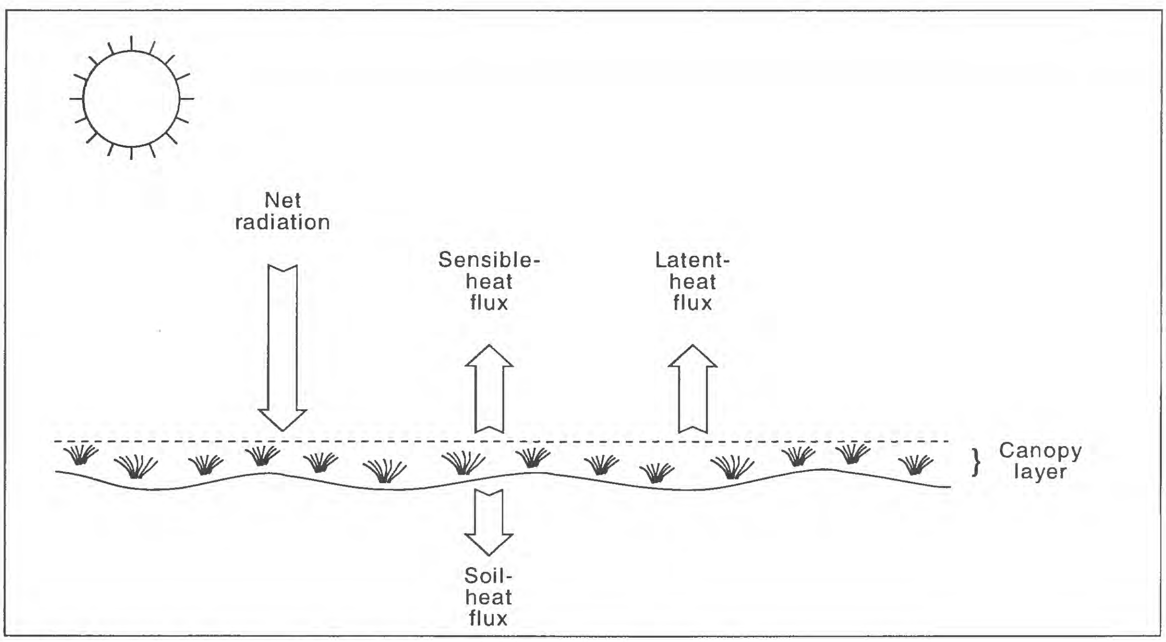


Figure 5.--Energy budget in the canopy layer.

Soil-heat flux, G (eq. 4), represents energy moving downward through the soil from the land surface or upward through the soil to the surface. Temperature gradients in the soil are represented by measurements from soil-heat flux transducers. The transducers measure the gradient across a material of known thermal conductivity. Although thermal conductivity of the soil changes with soil-moisture content and may differ from the transducer material, these differences produce small changes in the overall soil-heat flux and are ignored in this study. Soil-heat flux includes the amount of energy that is stored in, or comes from, the layer of soil between the surface and the point of measurement (eq. 5). In this report, soil-heat flux is considered positive when moving down through the soil from the land surface and negative when moving upward through the soil towards the surface.

Bowen-Ratio Method

The Bowen-ratio method incorporates energy-budget principles and turbulent-transfer theory (Brutsaert, 1982, p. 210-214). The ratio of sensible- to latent-heat flux is known as the Bowen ratio (Bowen, 1926). Bowen showed that this ratio, β (eq. 6), could be calculated from vertical gradients of temperature and vapor pressure over a surface (eq. 7) under certain conditions. Often the gradients are approximated from air-temperature and vapor-pressure measurements taken at two heights above the canopy. The Bowen-ratio method assumes that there is no net horizontal advection of energy. With this assumption, the coefficients (eddy diffusivities) for heat and water vapor transport, K_h and K_w, respectively, are assumed to be equal. Under advective conditions, K_h and K_w are not equal (Verma and others, 1978; Lang and others, 1983) and the Bowen-ratio method fails to accurately estimate ET. With the assumption that K_h and K_w are equal (eq. 8) and the combining of several terms to form the psychrometric constant (eq. 9), the Bowen ratio takes the form of equation 10. Once the Bowen ratio is determined, the energy-budget equation (eq. 1) can be solved for the sensible-heat flux (eq. 11) and latent-heat flux (eq. 12).

ET can then be determined using the latent-heat flux, latent-heat of vaporization of water, and a factor (86.4) that accounts for the conversion of units (eq. 13a). The conversion and factor are derived as follows. Given that LE is in units of watts per square meter (W/m^2), which is equivalent to joules per second per meter ($J/s/m^2$), that L is in units of joules per gram (J/g), that there are 8.64×10^4 seconds in a day (24 hours/day x 60 minutes/hour x 60 seconds/hour), and that $1 \times 10^{-6}\ m^3$ of water equals 1.0 g, then

$$\left[\left(J/s/m^2\right)/(J/g)\right] \times [8.64 \times 10^4\ s/d] \times [1.0 \times 10^{-6}\ m^3/g] \times [1.0 \times 10^3\ mm/m] = 86.4\ mm/day$$

One of the requirements for using the Bowen-ratio method is that the wind must move over a sufficient distance of similar vegetation and terrain before it reaches the sensors. This distance is termed fetch, and the fetch requirement is generally considered to be 100 times the height of the sensors above the surface (Campbell, 1977, p. 40). At the study sites, the maximum height that sensors were placed was 3.0 m above the canopy. Therefore, a distance of 300 m of similar vegetation and terrain should be present at the sites. This requirement was met at all sites. However, at the Black Rock Valley site, an abandoned field (in which the Bird Canyon site is located) begins about 400 m southwest of the site. Because winds often come from the southwest and wind speeds are frequently more than 7 m/s, there may have been some periods when the fetch requirement was greater than is generally accepted; in these cases, the Bowen-ratio method might not provide accurate estimates of ET. It is not certain whether the differences between the Bird Canyon grass site and the Black Rock Valley sagebrush site were sufficient to affect the data that were collected at the Black Rock Valley site. From October 1994 to September 1995, cumulative Bowen-ratio ET at the Black Rock Valley site was only 4 percent more than cumulative Bowen-ratio ET at the Bird Canyon site, suggesting that the differences between the two sites were small. There were some periods, however, when the differences in ET at the Black Rock Valley and Bird Canyon sites were large.

Penman-Monteith Method

Estimates of latent-heat flux made with the Penman-Monteith equation require values for vapor pressure (eq. 14), saturated vapor pressure (eq. 15), the slope of the saturated vapor-pressure curve (eq. 16), the aerodynamic resistance to heat (eq. 17), and the canopy resistance in addition to the energy-budget components of net radiation, soil-heat flux, and sensible-heat flux. Field measurements of air temperature, relative humidity, and wind speed are needed to determine these variables.

Penman (1948) was the first to introduce an evaporation equation for open water (Brutsaert, 1982, p. 215). Later, Penman (1956) described an equation to determine potential ET over any wet surface, wherein he made the assumption that atmospheric resistances to turbulent transport of heat equalled those of water vapor. The Penman equation (eq. 18) has been refined over the years (Monteith, 1965) and can estimate potential ET relatively accurately under conditions of unlimited water supply, such as occurs over bodies of water and well-watered, physiologically active crops. However, estimates of actual ET made with the Penman method for most wildland conditions would be in error because of a limited water supply.

Variations of the Penman equation account for the resistance due to plant stomatal closure, plant senescence, and partially dry soil, and they enable actual ET to be calculated when water is in limited supply. One variation developed by Monteith (1963b; 1965), termed the Penman-Monteith equation (eq. 19), adds a canopy resistance term (eq. 20) to the basic Penman equation. This canopy resistance, along with the aerodynamic resistance to heat, are the transport resistances over the plant canopy.

Canopy Resistance

As it is used in this report, the canopy resistance, r_c, is a combination of the resistances to evaporation due to dry soil and to transpiration due to stomatal closure or senescence. The canopy resistance is not easily measured, however. In practice, the canopy resistance is not measured directly, but determined by computing the latent-heat flux by other means, such as the Bowen-ratio method, for short periods, and then solving the Penman-Monteith equation for the canopy resistance (eq. 20), which was the approach used in this study. This approach is similar to that used by Russell (1980) to determine the canopy resistance as a function of the aerodynamic resistance to heat and the ratio of latent-heat flux to potential latent-heat flux, LE/LE_p. Using the Bowen-ratio method to calibrate the Penman-Monteith method for the canopy resistance, values for the canopy resistance ranged from near zero during and shortly after periods of heavy rainfall to over 5,000 seconds per meter (s/m) during extremely hot, dry periods. Because the canopy resistance is used as a calibration factor, it can include errors from a variety of sources. Measurement errors, if any, of net radiation, soil-heat flux, wind speed, air temperature, and vapor pressure can also affect the quality of the canopy resistance value.

For periods when Bowen-ratio data were available to calibrate the Penman-Monteith equation for the canopy resistance, daily average canopy resistances were computed with canopy resistances calculated for each 20-minute or 60-minute interval from 8 a.m. to 5 p.m., when ET was highest (Tomlinson, 1994, p. 20-24; Tomlinson, 1995, p. 21-26; Tomlinson, 1996a). This daily average canopy resistance was then used in the Penman-Monteith equation for all intervals, along with data for all the other needed parameters for each interval, to compute a daily ET value. This procedure allowed ET estimates to be made for days when Bowen-ratio data were available for only part of the day. For example, if Bowen-ratio latent-heat fluxes were very large positive or negative numbers in the morning (possibly due to ice on the cooled-mirror hygrometer), but the fluxes appeared accurate in the afternoon (after the ice melted), then only those afternoon latent-heat fluxes were used to calculate the average daily canopy resistance.

For the Black Rock Valley site, during periods when no Bowen-ratio data were available, such as the 1992-93 winter, daily canopy resistances for the Penman-Monteith method were estimated. During periods of rain or fog, the canopy resistance was assumed to be zero (unlimited water availability at, or approaching, potential ET conditions). This assumption seemed reasonable because, during heavy rainfall in the growing season, the canopy resistances calibrated by the Bowen-ratio method were usually near zero. Daily canopy resistances were increased about 100 to 500 s/m each subsequent day after precipitation, up to a maximum of 5,000 s/m. This seemed a reasonable maximum canopy resistance for a dry soil surface at this time of year, compared with canopy resistances calculated in August, when plants were approaching dormancy and surface soil moisture was not entirely depleted. These methods of estimation were used because no simple function was found to correlate canopy resistance with any one variable. At a semiarid site in Snively Basin on the ALE Reserve, canopy resistance correlated best with soil moisture, but the r^2 (square of the correlation coefficient) was only 0.63 (Tomlinson, 1995, p. 21). Because of the estimation methods that were used, errors in daily canopy resistance and ET are possibly high for winter values. However, errors in cumulative ET from November to March may be low when compared with cumulative ET for the year. At the Black Rock Valley site, the November-to-March period is over 40 percent of the year time-wise, but only about 21 percent of the annual ET occurs then.

The agreement of the Penman-Monteith calculations with the Bowen-ratio calculations for days with changing conditions, such as developing or lapsing rain, was increased by accounting for such conditions. For example, when rain fell for only part of a day, the canopy resistance for the time intervals when it was raining ($r_c = 0$) was different from the ones used in the time intervals when it was not ($r_c > 0$). The changes in canopy resistance during rainy periods were incorporated in the ET calculations because the changes in that variable can be large—more than 1,000 percent in some cases—from non-rainy periods in the same day. Using a straight-line average canopy resistance for days with rain would often produce erroneously high estimates of latent-heat flux and ET with the Penman-Monteith method, compared with the Bowen-ratio method. These result from the daily-average canopy resistance being skewed by low values of canopy resistance during the short periods of rain.

The canopy resistance was the overall calibration factor between the Bowen-ratio and Penman-Monteith methods of estimating ET. The resistance incorporates errors from a variety of sources. These errors appear to average out for the most part, however, with generally good agreement between Bowen-ratio and Penman-Monteith latent-heat fluxes.

Aerodynamic Resistance

In the Penman and Penman-Monteith equations, the aerodynamic resistance to heat, r_h, is the turbulent resistance between the average height of leaf surfaces and the height of temperature and wind-speed measurements. Heat produced at the leaf surfaces must overcome this resistance to arrive at sensor height.

There are a number of ways to calculate aerodynamic resistance to heat. These methods commonly use momentum-exchange theory and can produce different estimates of the resistance. Momentum-exchange theory is complex, and some of the accurate measurements needed to estimate aerodynamic resistance are difficult to obtain. Some methods are applicable only to neutral periods (sensible-heat flux, H, = 0), others only to stable periods $(H < 0)$, or unstable periods $(H > 0)$. A primary goal in this study was to use a method of calculating r_h that was simple to apply and, when used in the Penman-Monteith method, would produce reasonable estimates of ET compared with estimates from the Bowen-ratio method.

The equation used in this study to estimate r_h (eq. 17) requires the measurement of wind speed at only one height. However, the equation is only applicable during neutral conditions. For unstable conditions, a profile stability correction for sensible heat is required. However, solving for a profile stability correction involves a series of complex, iterative calculations. Though using equation 17 without the correction for unstable conditions may overestimate r_h by as much as a factor of two in some conditions (D.I. Stannard, U.S. Geological Survey, written commun., 1992), some investigators have produced reasonable results without using a stability correction in their calculations for wildland ET (Duell, 1990). Some researchers have applied the correction and found little effect on the resulting estimates of r_h (Nichols, 1992). Others have sought to obtain an empirical equation that incorporates this term (Thom and Oliver, 1977; Marht and Ek, 1984).

For this study, using an r_h value in error by as much as 100 percent had little impact on the calculations of ET. Doubling r_h for all time steps (20 or 60 minutes) in the Penman-Monteith equation for 35 days in May, June, and July 1992 increased the daily average r_c by 30 percent and decreased the daily ET estimates by an average of 3.8 percent, which is within range of the precision errors of the instruments (Tomlinson, 1995, p. 14-15). Furthermore, the data showed that the canopy resistance, r_c, frequently varied by 30 percent or more between successive 20- or 60-minute time steps, even during neutral conditions. Using the stability correction in this study would not have resulted in more accurate estimates of ET so it was not used.

The 30-percent error in r_c is a worst-case scenario; the error is likely much less than 30 percent most of the time, because neutral conditions are often approximated with high wind speeds (D.I. Stannard, U.S. Geological Survey, written commun., 1990), which are common at the study sites. Hourly average wind speeds frequently range from 5 to 10 m/s, occasionally exceeding 15 m/s. Wind speeds were determined at height z, which was 3.0 m above the canopy.

The terms d, z_m, and z_h in equation 17 are used in wind-profile equations. The zero plane displacement height, d, is the distance, in meters, from the surface to the mean height of heat, vapor, or momentum exchange. The momentum roughness length, z_m, in meters, is related to the variance in canopy height. The heat-transfer roughness length, z_h, in meters, is a function of the momentum roughness length. The terms d, z_m, and z_h are difficult to measure, but they may be determined graphically from wind profiles or calculated through empirical equations.

For the Black Rock Valley site, no wind-speed profile measurements were made to determine z_m. Estimates of z_m over 0.75-m high greasewood in Nevada (Nichols, 1992, p. 229-233) were 0.07 m from a Leaf-Area-Index (total leaf area per unit area of land surface) method and 0.06 m using wind-speed profiles. From an analysis of turbulence over a sparsely vegetated canopy with 1-m-high greasewood in Colorado, z_m was estimated at 0.05 m (Stannard, 1993, p. 1381-1383). An average of 0.06 m seems reasonable to use for the Black Rock Valley site because of the similarity in canopy height—the average shrub height at the Black Rock Valley site was 0.9 m, compared with 0.75 m and 1 m at the Nevada and Colorado sites, respectively. The value for z_h at the Black Rock Valley site was estimated from

$$\ln\left(\frac{z_m}{z_h}\right) = 2$$ (Garratt and Hicks, 1973, fig. 2). This

method has been used at other sparse-canopy sites (Stannard, 1993, p.1383). The zero-plane displacement, d, was estimated at zero for the Black Rock Valley site because of the wide spacing of the shrubs and sparseness of the grasses. From the above estimated values for d, z_m, and z_h for a height z of 3.0 m above the canopy, equation 17 for the Black Rock Valley site becomes

$$r_h = \frac{145}{u} .$$

Estimates of d, z_m, z_h, and r_h were not made for the Bird Canyon or Firewater Canyon sites because the Penman-Monteith method was not used to estimate ET at those sites.

RESULTS

Energy budgets, ET values, and comparisons of ET computed using different methods and sites were used to determine and evaluate the results of the study. Using the Bowen-ratio and Penman-Monteith methods, energy-budget components of sensible- and latent-heat flux were determined. ET was estimated as part of the latent-heat flux, as calculated using equation 1. For estimates from the Bowen ratio and Penman-Monteith methods, averages of all net radiometer values and soil-heat flux values at each site were used to provide a more representative value of net radiation and soil-heat flux at each site and a more detailed comparison of ET between the methods. Thus, the differences between the ET estimated by the methods are due to reasons other than small differences in net radiation or soil-heat flux. Bowen-ratio ET estimates agreed with Penman-Monteith ET estimates and with ET estimates made using fixed-sensor instruments.

ET values and comparisons provided some similar and some contrasting results at each site. Seasonal patterns of ET were similar at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites but comparisons of daily ET at each of the sites showed there were many daily differences, some of them over 100 percent. At the Black Rock Valley and Bird Canyon sites, seasonal and annual totals of ET were very similar. However, seasonal and annual totals of ET at the Firewater Canyon site averaged about 30 percent less than totals at the Black Rock Valley and Bird Canyon sites. Comparisons of cumulative ET and precipitation for the period October 22, 1994, to September 5, 1995, for the Black Rock Valley, Bird Canyon, and Firewater Canyon sites showed that cumulative ET was 136, 139, and 97.3 percent of cumulative precipitation, respectively. These comparisons suggest that the Black Rock Valley and Bird Canyon sites receive water for ET not only from precipitation but from runoff and/or ground-water flow from upland areas.

Energy Budgets

In energy budgets for the study sites, net radiation equals the sum of the soil-heat, sensible-heat, and latent-heat fluxes (eq. 1). The variability of these energy- budget fluxes depends on many factors: vegetation (type, height, and extent), stage of plant growth, amount and density of cloud cover, precipitation, wind speed, season of the year, and soil-moisture content. Some plant canopies, such as forests, can also store large amounts of heat that can be part of the energy budget. Canopy heat storage for the Black Rock Valley, Bird Canyon, and Firewater Canyon sites was considered negligible because of the sparse nature and short height of the canopies. Figures 6-17 show selected energy budget plots for a variety of conditions in the period of study at the Black Rock Valley site.

Net radiation showed considerable variability, depending on cloud cover and season of the year. On clear days, such as May 10, 1992 (fig. 7), May 24 and 26, 1993 (figs. 8-9), January 28 to February 1 and February 8, 1994 (fig. 13), and August 24, 1994 (fig. 15), net radiation peaked around noon and measured near zero at sunrise and sunset. The smoothness of net radiation was also generally reflected in the other fluxes. Net radiation on partly cloudy days, such as May 30 to June 8, 1993 (figs. 9-10), June 26 to July 3, 1993 (figs. 11-12), and May 16-22, 1994 (fig. 14), was irregular due to clouds passing over the site. On completely cloudy days, such as June 9, 11, and 14, 1993 (fig. 10), October 26-27, 1994 (fig. 16), and April 10, 1995 (fig. 17), net radiation and other fluxes were low and somewhat irregular depending on the thickness of the cloud cover. On days of fog, such as February 2-7, 1994 (fig. 13), net radiation and other fluxes were extremely low, less than 80 W/m^2. During days of precipitation such as April 29, 1992 (fig. 6), July 22-23, 1992 (fig. 7), April 8 and May 15, 1994 (fig. 14), and April 12 and September 6-7, 1995 (fig. 17), daytime net radiation and other fluxes remained very low, sometimes less than 100 W/m^2. (Text continued on p. 30.)

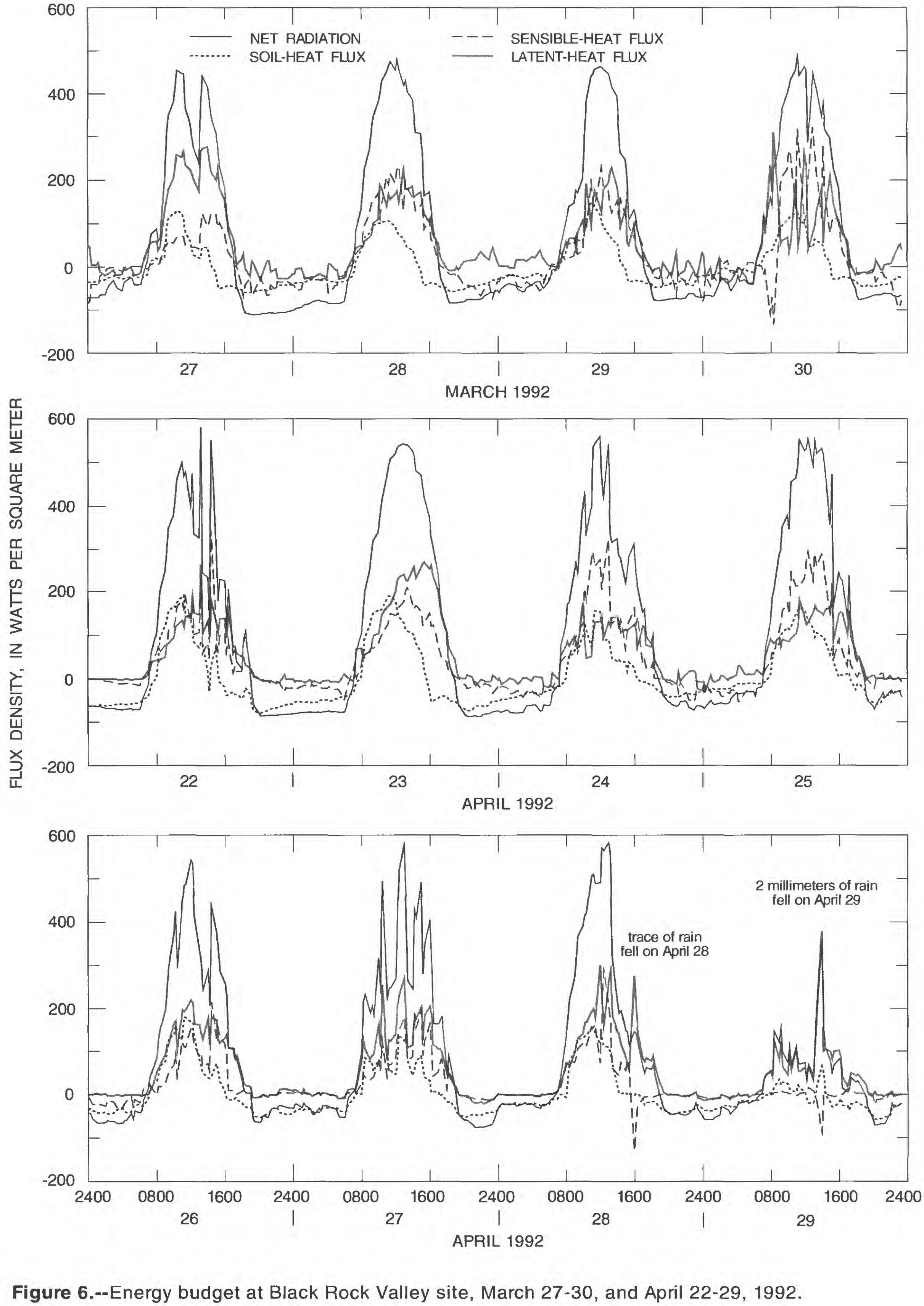


Figure 6.--Energy budget at Black Rock Valley site, March 27-30, and April 22-29, 1992.

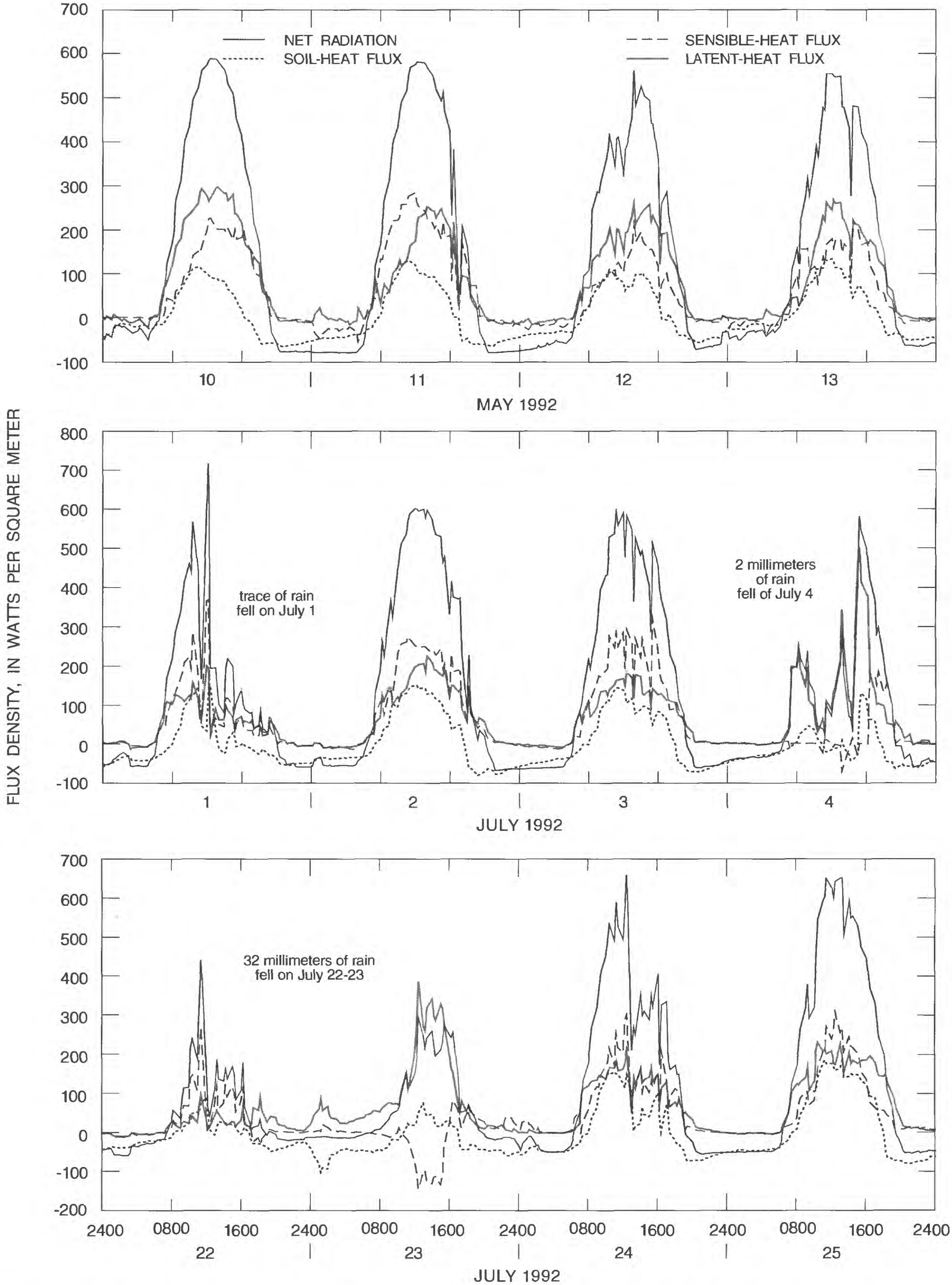


Figure 7.--Energy budget at Black Rock Valley site, May 10-13, July 1-4, and July 22-25, 1992.

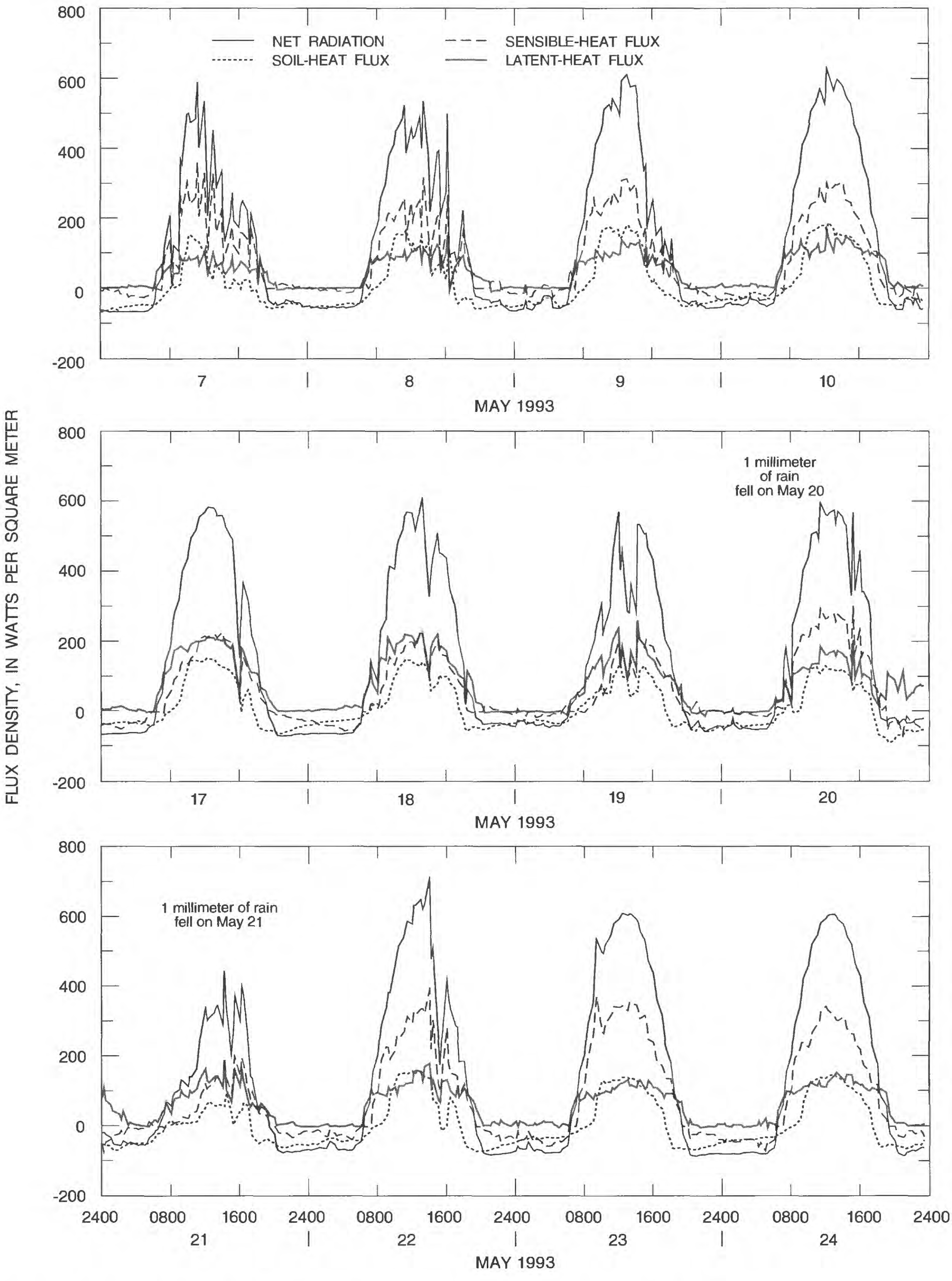


Figure 8.--Energy budget at Black Rock Valley site, May 7-10, and May 17-24, 1993.

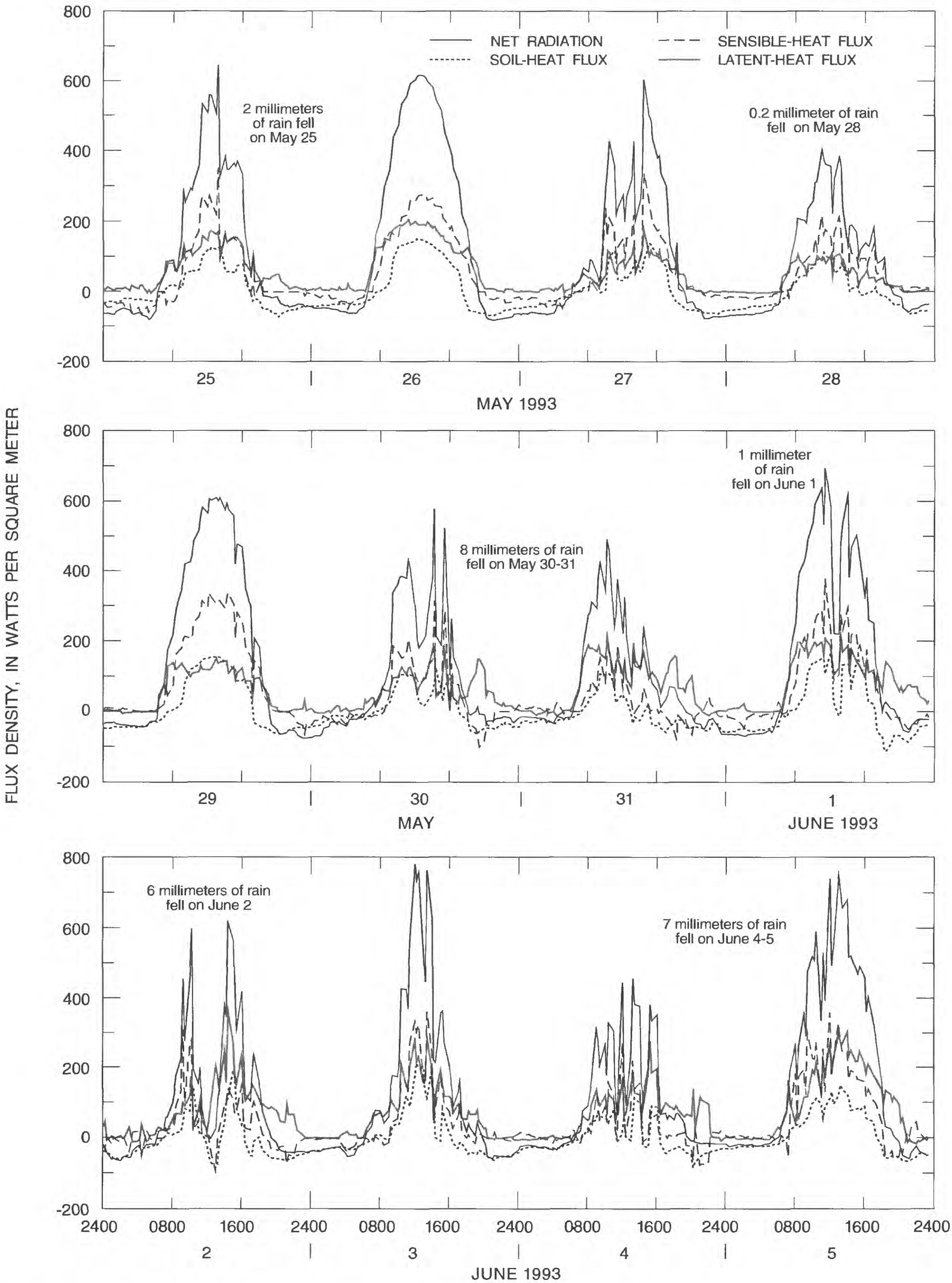


Figure 9.--Energy budget at Black Rock Valley site, May 25 to June 5, 1993.

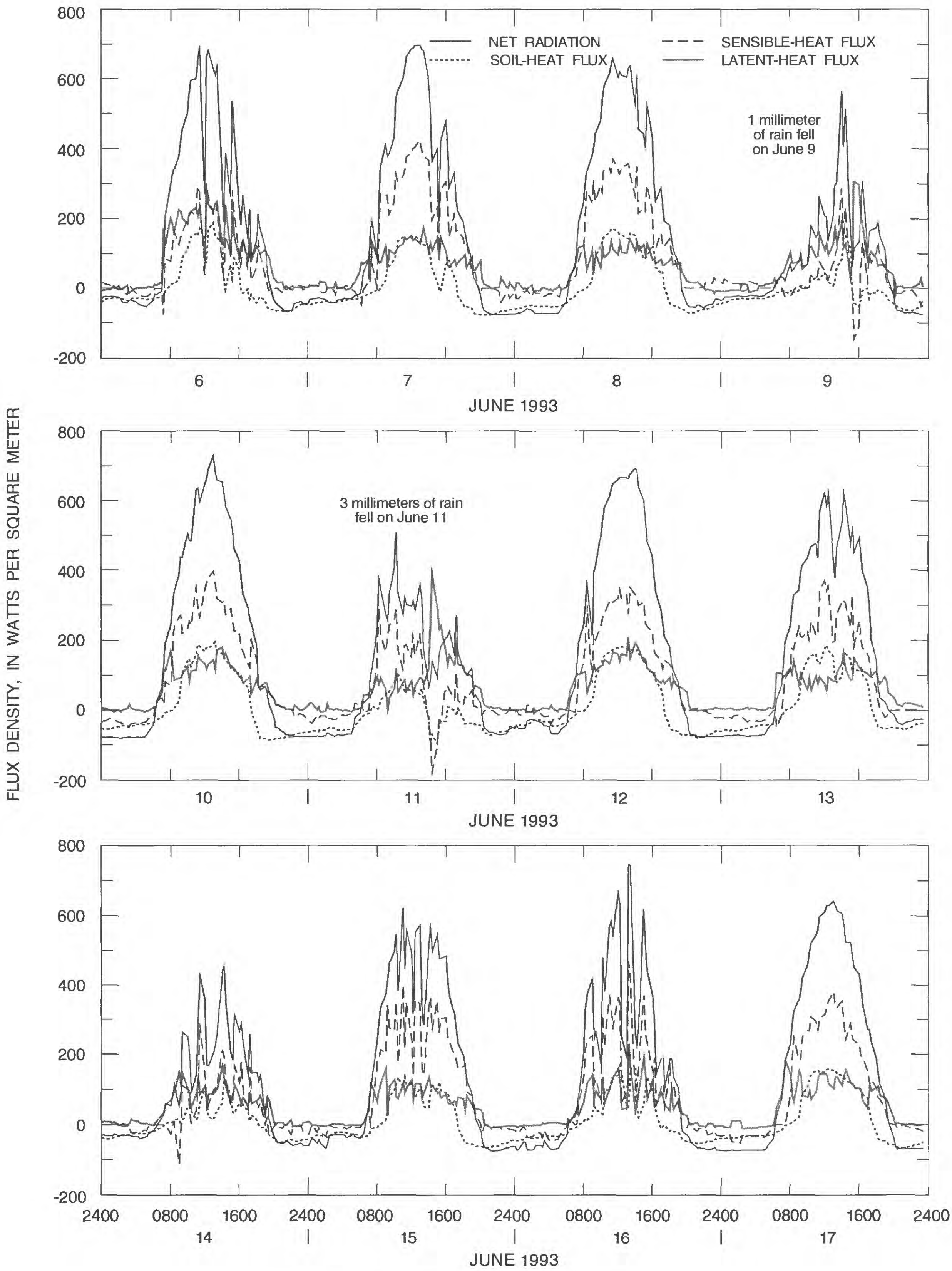


Figure 10.--Energy budget at Black Rock Valley site, June 6-17, 1993.

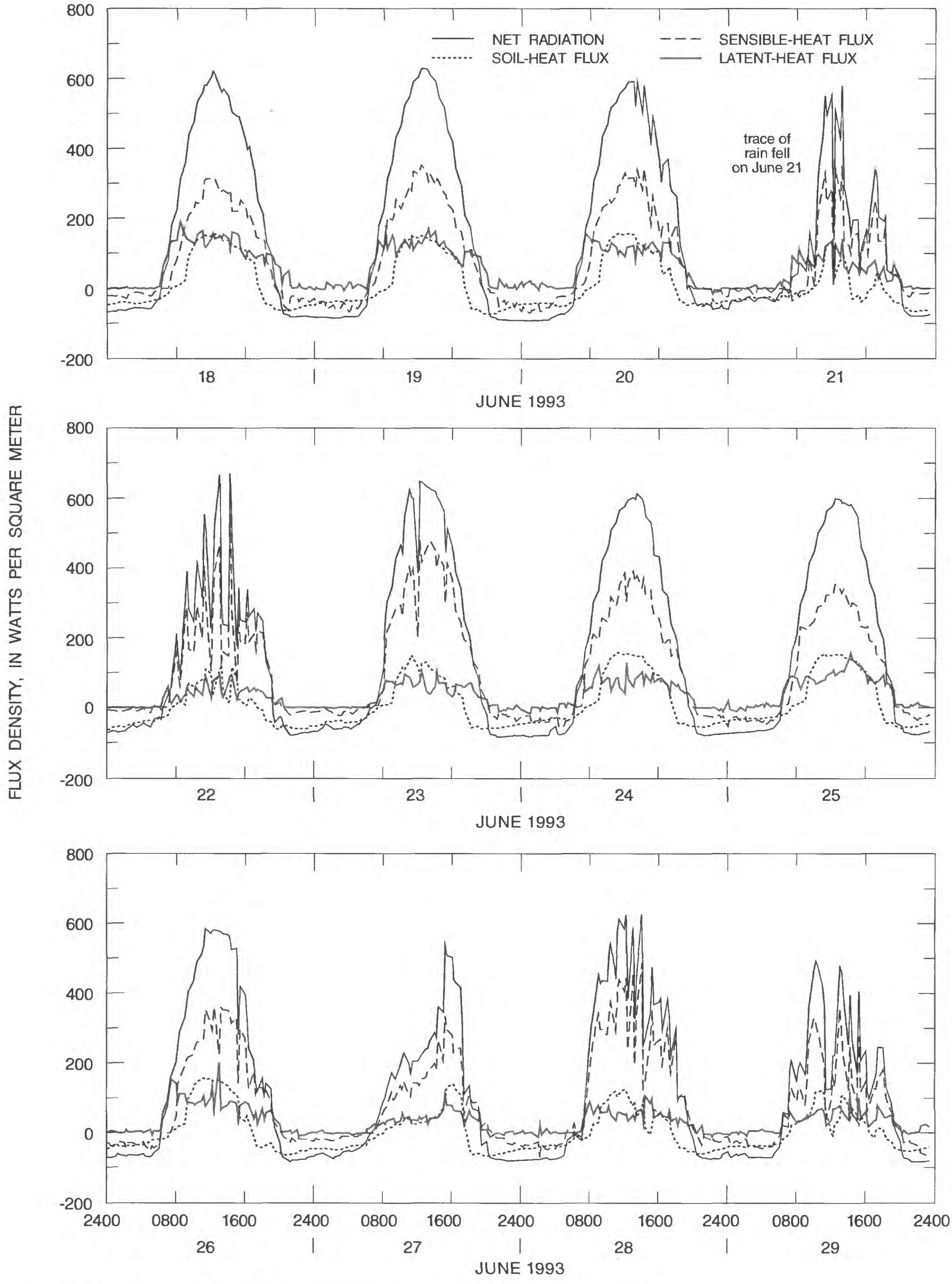


Figure 11.--Energy budget at Black Rock Valley site, June 18-29, 1993.

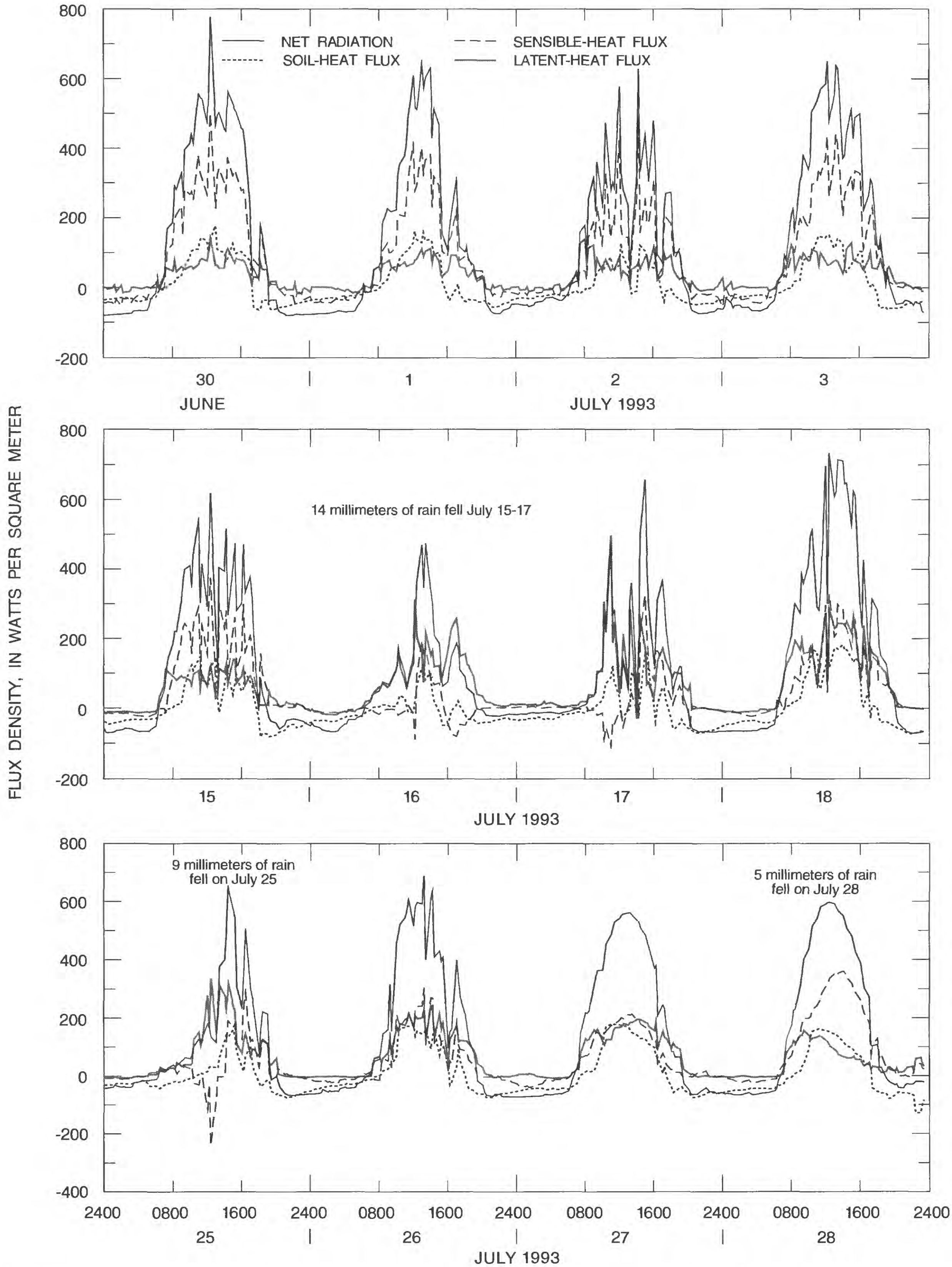


Figure 12.--Energy budget at Black Rock Valley site, June 30 to July 3, July 15-18, and July 25-28, 1993.

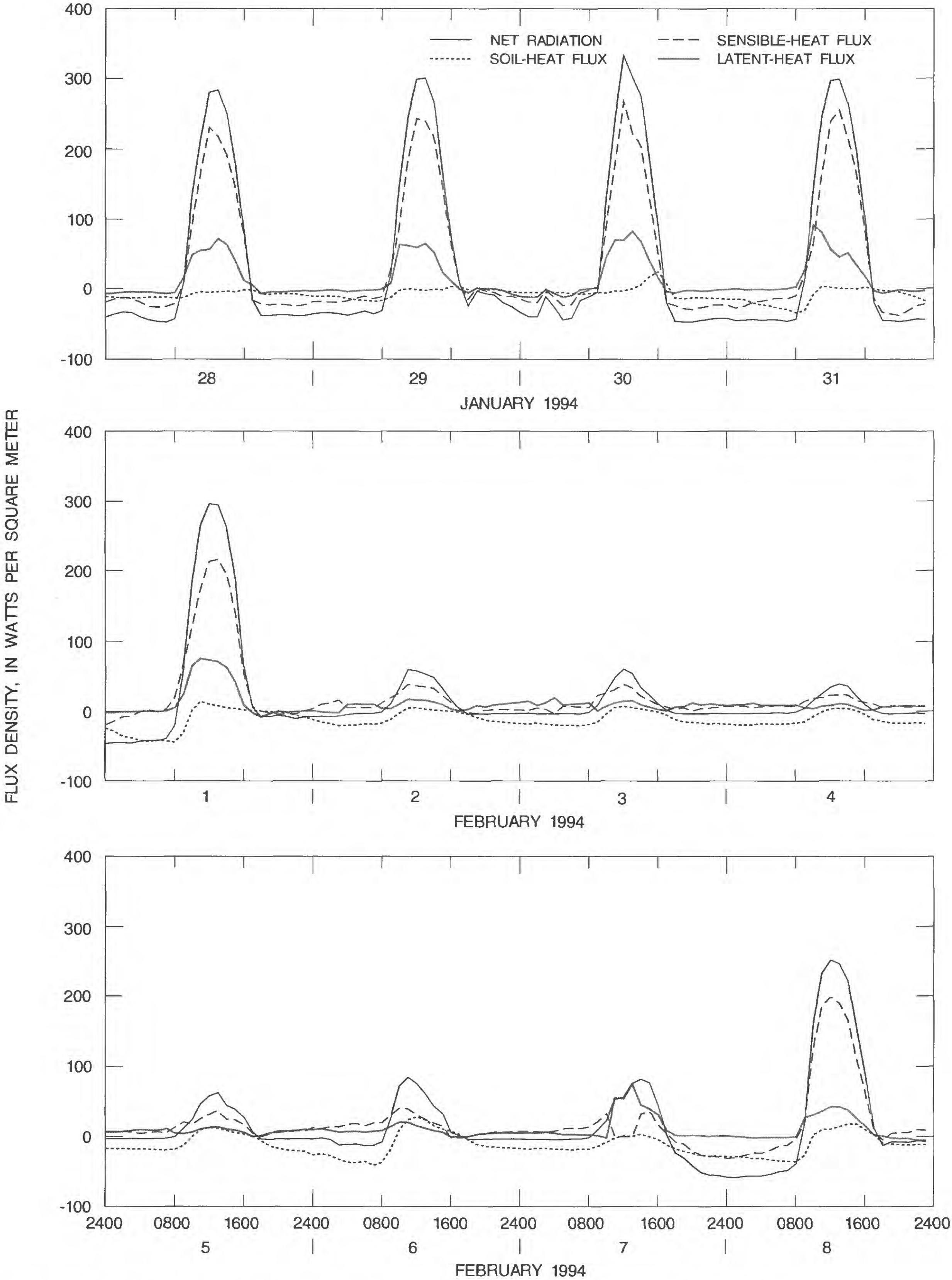


Figure 13.--Energy budget at Black Rock Valley site, January 28 to February 8, 1994.

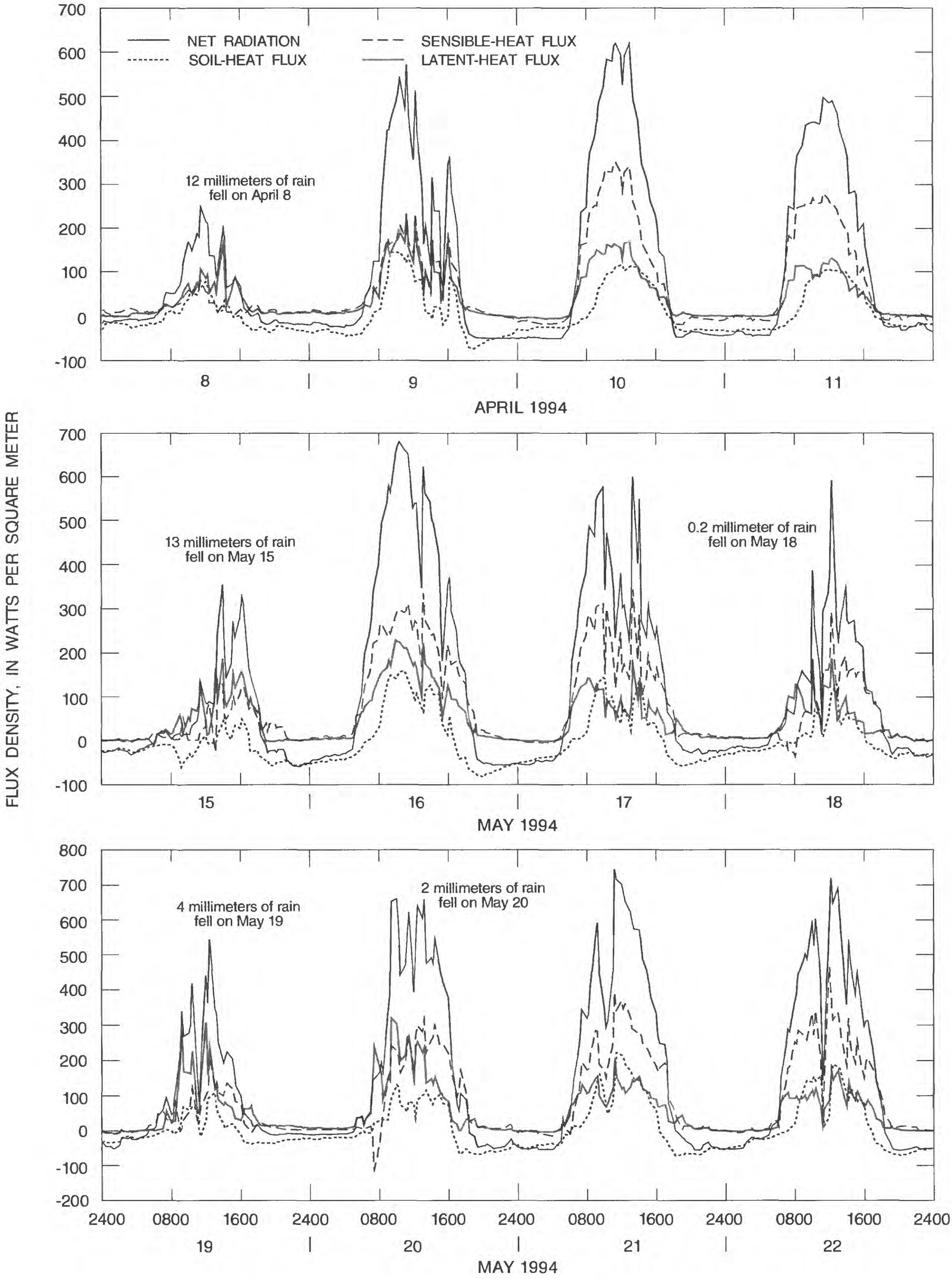


Figure 14.--Energy budget at Black Rock Valley site, April 8-11, and May 15-22, 1994.

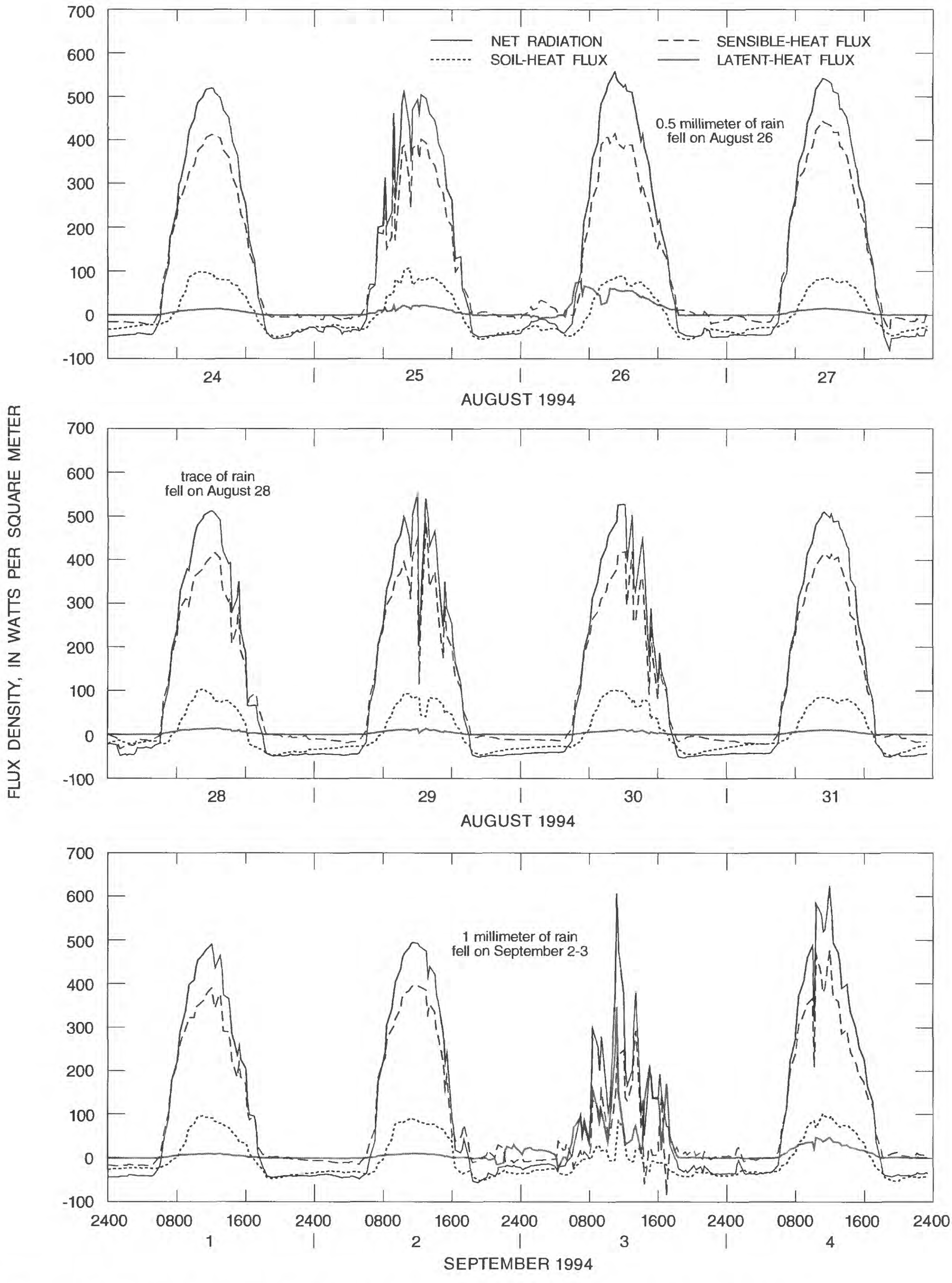


Figure 15.--Energy budget at Black Rock Valley site, August 24 to September 4, 1994.

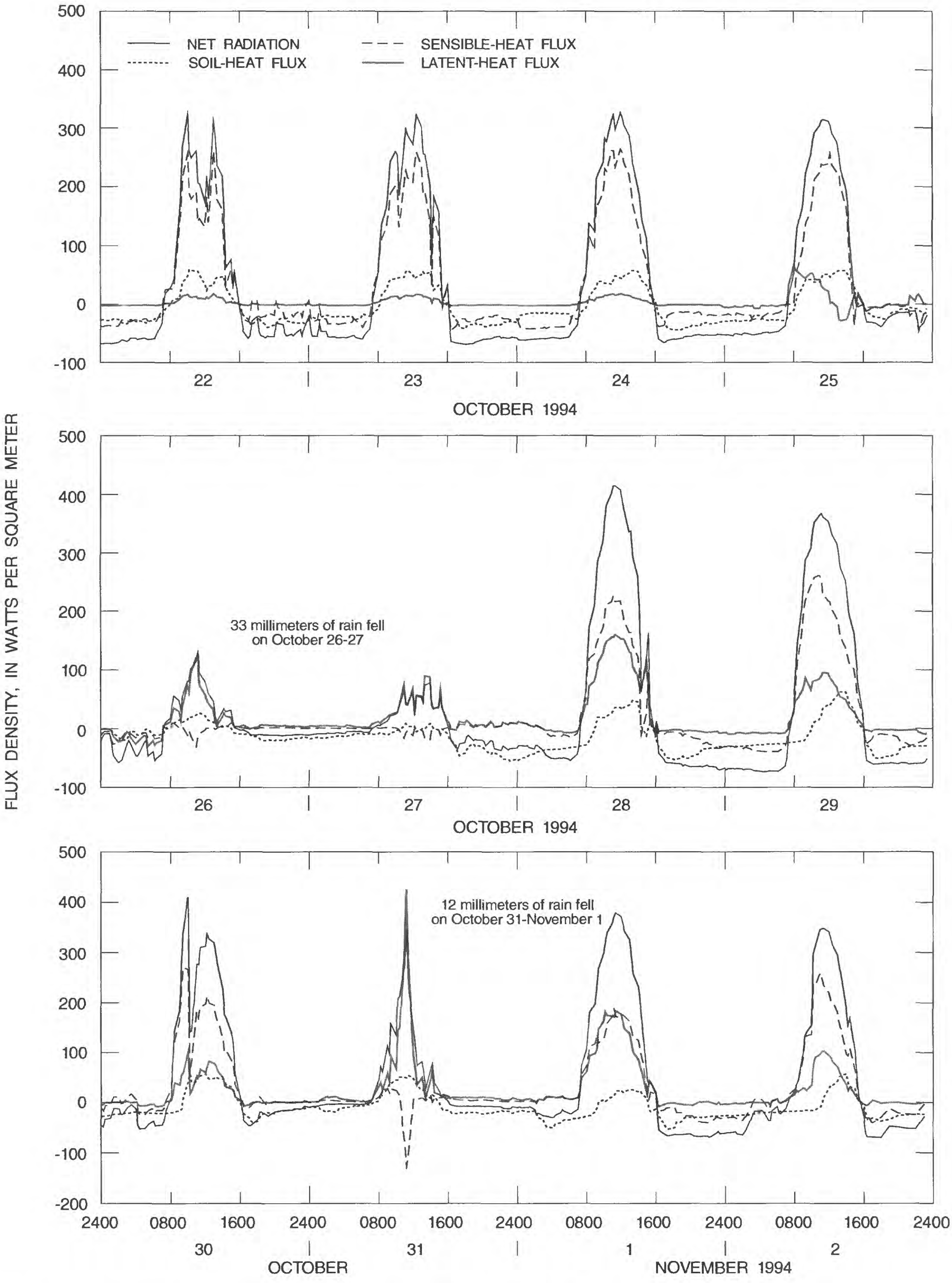


Figure 16.--Energy budget at Black Rock Valley site, October 22 to November 2, 1994.

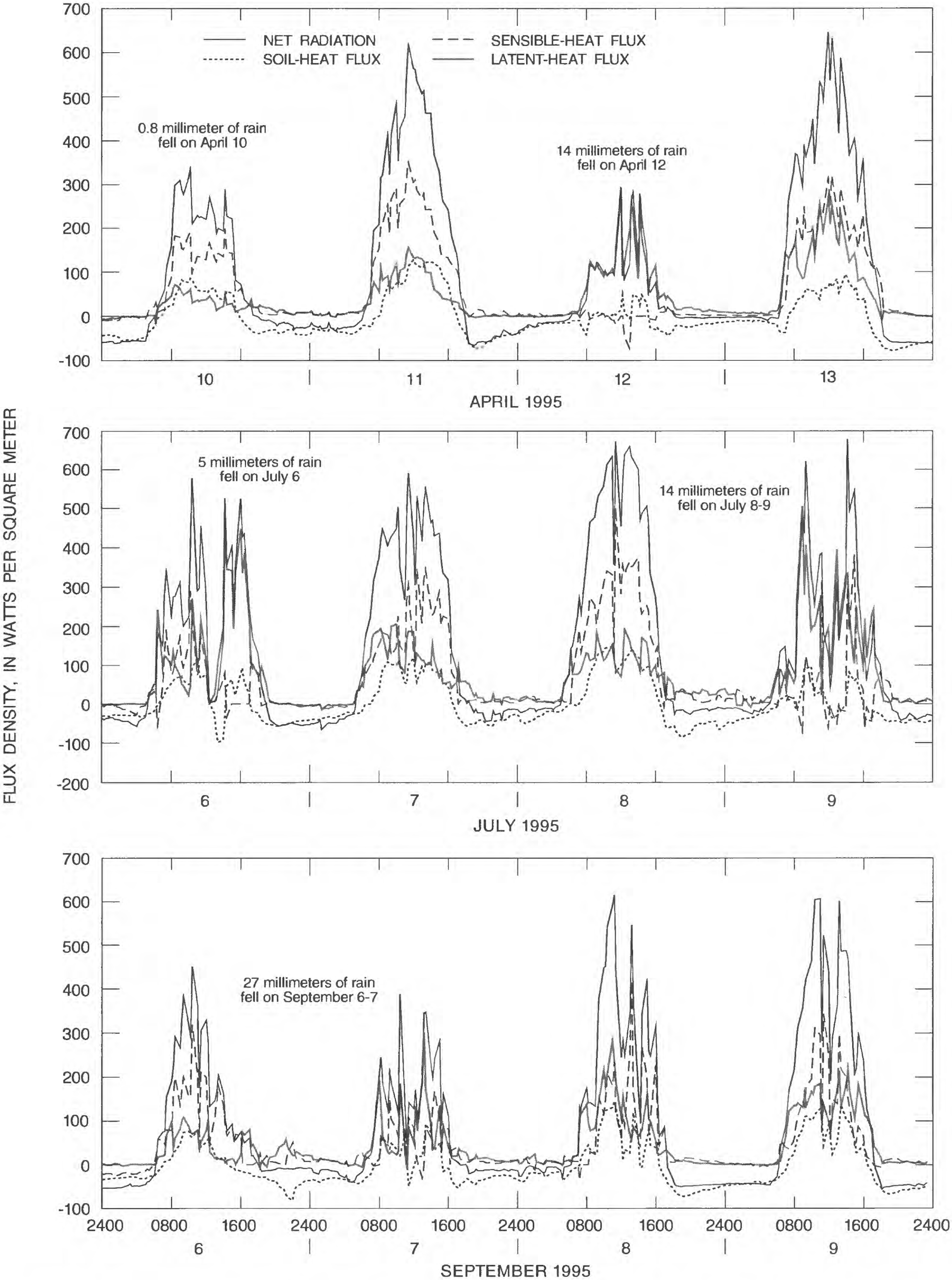


Figure 17.--Energy budget at Black Rock Valley site, April 10-13, July 6-9, and September 6-9, 1995.

The energy-budget plots show strong seasonal differences in net radiation. Net radiation on a clear day in winter (January 29, 1994, fig. 13) is only about 55 percent as much as on a clear day in spring (April 23, 1992, fig. 6) or 43 percent as much as on a clear day near the summer solstice (June 19, 1993, fig. 11). Different angles of the sun above the horizon during the different seasons probably account for most of these seasonal differences in net radiation; for latitude 47 degrees north, the approximate latitude of the study sites, the sun reaches a maximum angle of 20 degrees above the horizon at winter solstice and a maximum angle of 66 degrees above the horizon at summer solstice.

During days of heavy precipitation, such as July 23, 1992 (fig. 7), October 26-27, 1994 (fig. 16), and April 12, 1995 (fig. 17), soil-heat flux and net radiation produced little surface warming so that soil- and sensible-heat fluxes remained low. Most of the energy from net radiation was converted to ET; latent-heat flux approached, or in some cases exceeded, net radiation. For periods when latent-heat flux exceeded net radiation, such as July 23, 1992 (fig. 7), additional energy may have come from soil-heat flux or advected sensible-heat flux. Dramatic drops in the fluxes were sometimes noted during afternoon rainstorms, such as June 1 and 2, 1993 (fig. 9) and July 6, 1995 (fig. 17).

For periods when the top layer of soil and the air were extremely dry, such as August 24 to September 2, 1994 (fig. 15), and October 22-24, 1994 (fig. 16), most net radiation was partitioned to sensible-heat flux and, to a lesser extent, soil-heat flux. In these cases, sensible-heat flux approached net radiation, while the latent-heat flux approached zero. Exceptions occurred during these dry periods when a light rainfall produced a short increase in latent-heat flux, such as on August 26 and September 3, 1994 (fig. 15).

Latent-heat flux can be high at times without significant precipitation, as a result of plant transpiration and wind-induced evaporation from soil or intercepted water. In spring, when vegetation is in full growth (plant shoots are maturing and seed heads are starting to develop) transpiration is high and is reflected in high latent-heat flux (ET over 2 mm/day) even in the absence of substantial rainfall for several days (April 25-28, 1992, on fig. 6 and May 10-13, 1992, on fig. 7). High winds can produce high latent-heat flux even after only light rainfalls (May 20, 1993, on fig. 8 and June 1, 1993, on fig. 9).

Evapotranspiration at the Black Rock Valley Site

ET estimates were made on the basis of data from energy-budget flux calculations using the Bowen-ratio and Penman-Monteith methods. ET estimates at the Black Rock Valley site followed a seasonal pattern during 1992 to 1995 (fig. 18). Variations in the patterns resulted from environmental conditions particular to that year, such as precipitation and air temperature. Generally, the period of lowest ET occurred in late summer, fall, or winter during very dry or very cold conditions, while the period of highest ET occurred in late spring, coinciding with periods of peak plant growth above the soil surface (fig. 18; table 2). On average, 62 percent of the annual ET occurred during peak plant growth from April to July, 17 percent during the dry period from August to October, and 21 percent during winter, November to March, when plants are primarily growing roots. During the year, daily ET ranged from zero to over 4 mm. Bowen-ratio ET estimates generally compared favorably with Penman-Monteith and fixed-sensor ET estimates.

Comparison of Bowen-Ratio and Penman-Monteith Methods

The latent-heat flux calculated with the Bowen-ratio method was used to calibrate the Penman-Monteith equation for the canopy resistance. Canopy resistances for each 20- or 60-minute time step from about 8 a.m. to 5 p.m. were averaged for the day. Latent-heat flux and ET were then recalculated for each time step with that daily average canopy resistance and actual time-step values of all other parameters (like net radiation and air temperature, for example) in the Penman-Monteith method. For the Black Rock Valley site, this procedure produced generally satisfactory daily estimates of Penman-Monteith ET, compared to Bowen-ratio ET as determined by the square of the correlation coefficient ($r^2 = 0.91$, fig. 19). For example, from May 9-15, 1992, daily Penman-Monteith ET averaged only 6 percent more than daily Bowen-ratio ET (table 2). Bowen-ratio and Penman-Monteith latent-heat flux comparisons also show reasonably close agreement (figs. 20-21). These results were expected because the Bowen-ratio method was used to calibrate the Penman-Monteith method for the canopy resistance. The differences between results of the two methods mostly reflect the differences between the actual calibrated canopy resistance for each time step and the average daily canopy resistance used to recalculate ET in the Penman-Monteith equation. (Text continued on p. 46.)

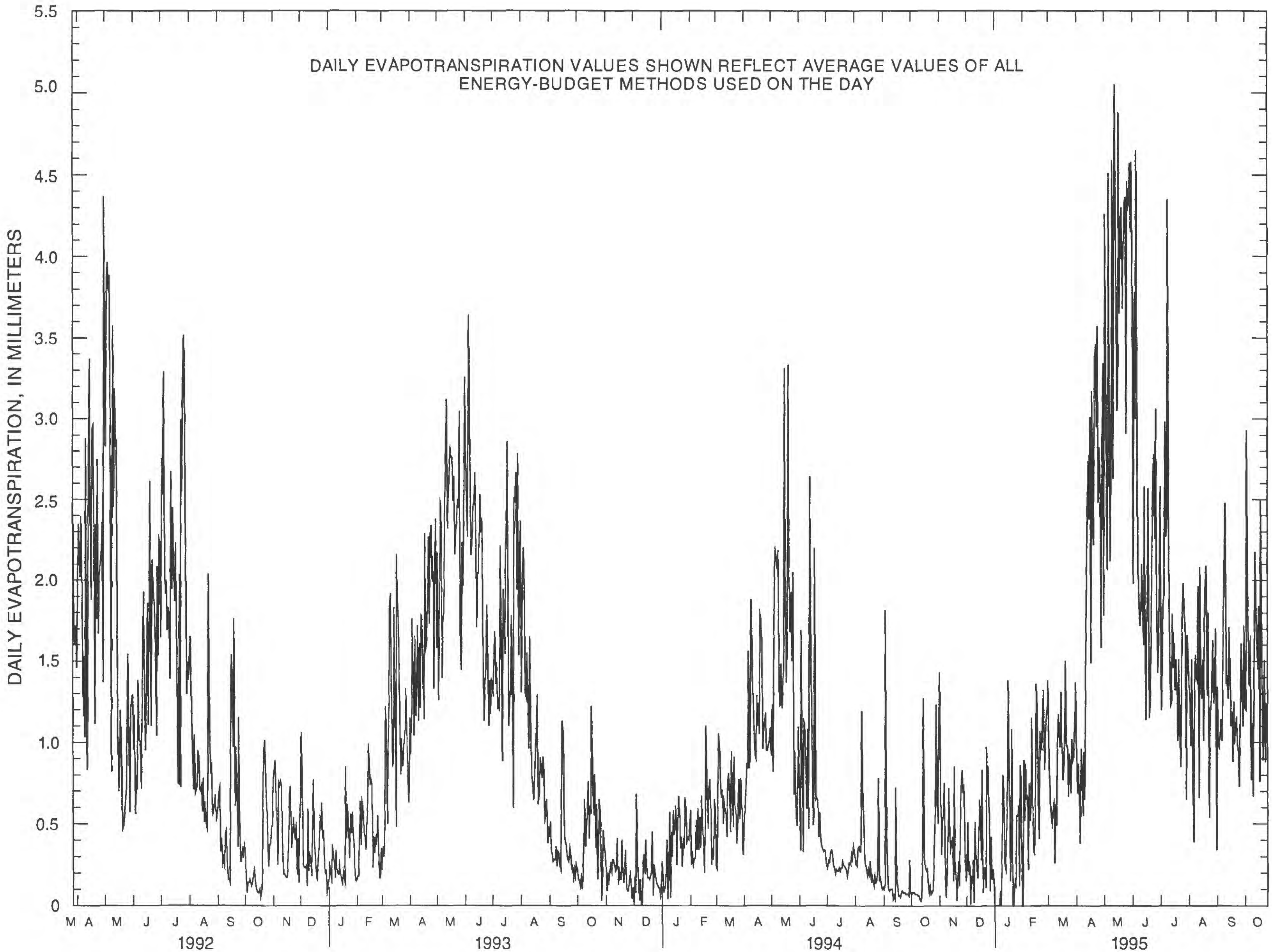


Figure 18.--Daily evapotranspiration at Black Rock Valley site, March 27, 1992 to October 24, 1995.

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994*

[mm, millimeters; PRC, precipitation; BR, evapotranspiration, Bowen-ratio method; PM, evapotranspiration, Penman-Monteith method; FX, evapotranspiration, Bowen-ratio method, using fixed-sensor instruments; TOT, monthly totals of daily precipitation and evapotranspiration; TR, data suggests trace of precipitation; *, estimated or partly estimated; #, precipitation at Moxee City (National Oceanic and Atmospheric Administration, 1992, 1993, 1994); --, insufficient data to calculate daily or monthly value]

	March 1992			April 1992			May 1992		
Day	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)
1	--	--	--	0.00	1.82	--	0.00	3.29	3.53*
2	--	--	--	0.00	2.35	--	0.00	2.73	2.93*
3	--	--	--	0.00	2.16	--	0.00	3.71	3.98*
4	--	--	--	TR	2.02	--	0.00	3.83	4.10*
5	--	--	--	0.00	2.40	--	0.00	3.66	3.92*
6	--	--	--	0.00	1.99	--	0.00	3.75	4.02*
7	--	--	--	0.00	1.16	--	0.00	2.92	3.13*
8	--	--	--	0.00	1.53	--	0.00	0.79*	0.85*
9	--	--	--	9.40#	1.03	--	0.00	2.30	2.24
10	--	--	--	0.51#	2.88	--	0.00	3.51	3.64
11	--	--	--	TR	0.83	--	0.00	2.40	2.51
12	--	--	--	3.30#	1.02*	--	0.00	2.82	3.55
13	--	--	--	15.75#	2.82	--	0.00	2.72	2.96
14	--	--	--	0.00	3.37	--	0.00	2.80	2.91
15	--	--	--	TR	2.41	--	0.00	1.06*	1.01
16	--	--	--	3.05#	1.88	--	0.00	--	0.70
17	--	--	--	TR	2.94	--	0.00	--	0.91
18	--	--	--	0.00	2.96	--	0.00	--	1.20
19	--	--	--	0.00	2.44	--	0.00	--	0.95
20	--	--	--	0.00	1.11	--	0.00	--	0.47
21	--	--	--	0.00	2.35	--	0.00	--	0.49
22	--	--	--	0.00	1.76	--	0.00	--	0.57
23	--	--	--	0.00	2.75	--	0.00	--	0.62
24	--	--	--	0.00	1.67	--	0.00	--	0.73
25	--	--	--	0.00	2.01	--	2.54	1.03	1.23
26	TR	--	--	0.00	2.10	--	0.00	1.51	1.58
27	0.00	2.49	--	0.00	2.19	--	0.00	--	0.90
28	0.00	1.82	--	TR	2.36	--	0.00	--	0.57
29	0.00	1.60	--	2.03#	1.37	--	TR	--	1.22
30	0.00	1.72	--	TR	4.37	--	0.00	--	1.28
31	0.00	1.46*	--				0.00	1.26	1.31
TOT	--	--	--	34.04#	64.05	--	2.54	--	60.01*

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	June 1992			July 1992			August 1992		
Day	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)
1	TR	0.98	0.93	TR	1.61	1.68	0.00	--	1.59
2	0.00	--	1.17	0.00	2.58	2.93	0.00	--	1.65
3	0.00	--	0.56	0.00	2.26	2.80	0.00	--	1.26
4	0.00	--	0.77	1.78	3.11	3.47	0.00	0.93	0.90
5	0.00	--	0.74	0.00	2.55	2.31	TR	0.65	0.77
6	0.00	1.28	1.49	TR	1.80	2.03	TR	1.00	1.09
7	0.00	1.05	0.98	TR	1.86	2.14	0.00	0.64	0.74
8	0.00	1.05	0.96	0.00	1.42	1.96	0.00	0.69	0.73
9	0.00	0.73	0.70	0.00	1.57	2.09	0.00	0.68	0.77
10	0.00	1.16	1.19	TR	1.99	1.50	0.00	--	0.95
11	0.00	1.54	1.71	0.00	1.25	1.53	0.00	--	0.90
12	11.18	--	1.93	0.00	2.49	2.85	0.00	--	0.71
13	0.76	--	1.17	0.00	2.06	1.83	0.00	--	0.70
14	0.00	--	0.95	0.00	2.13	2.77	0.00	0.66	0.80
15	0.00	--	1.45	0.00	1.77	2.25	0.00	0.50	0.65
16	0.00	--	1.86	0.00	1.64	2.10	0.00	--	0.78
17	0.00	1.05*	1.16	0.00	2.07*	2.40	0.00	0.51	0.51
18	0.00	1.65	1.82	TR	1.51*	1.67	0.00	0.58	0.69
19	0.00	2.37	2.86	0.25	0.66	.84	0.00	0.50	0.49
20	0.00	1.12	1.08	0.00	0.59*	.90	0.00	--	0.47
21	0.00	1.64	1.79	0.00	1.94	2.13	2.79	--	0.82
22	0.00	--	2.13	0.76	0.71*	0.74	3.56	2.04	2.04
23	0.00	--	1.91	31.50	3.26	2.73	0.00	1.10	1.15
24	0.00	--	1.84	0.00	2.41	2.69	0.00	0.82	0.80
25	0.00	1.50	1.70	0.00	3.12	3.58	0.00	0.82	0.87
26	0.00	0.98*	1.10	0.00	3.13	3.90	0.00	0.54	0.58
27	TR	1.84	2.33	0.00	2.38*	3.68	0.00	0.55	0.60
28	7.87	1.43	1.64	0.00	1.71*	2.82	0.00	0.63	0.63
29	0.25	2.20	2.31	0.00	1.12*	1.47	0.00	0.58	0.78
30	0.51	2.12	2.34	0.00	1.49*	1.49	0.00	0.52	0.51
31				0.00	1.33*	1.44	0.00	0.52	0.62
TOT	20.57	--	44.57	34.29	59.52*	68.72	6.35	--	26.55

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

Day	September 1992			October 1992			November 1992		
	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)
1	0.00	--	0.59	0.00	--	0.34	1.78	--	0.77
2	0.00	--	0.69	0.00	--	0.17	0.25	--	0.84
3	0.00	--	0.72	0.00	--	0.08	0.00	--	0.89
4	0.00	--	0.33	0.00	--	0.14	4.32	--	0.68
5	0.00	--	0.41	0.00	--	0.14	0.00	--	0.47
6	0.00	--	0.26	0.00	--	0.16	0.00	--	0.25
7	0.00	--	0.29	0.00	--	0.14	1.52	--	0.75
8	TR	--	0.25	0.00	--	0.12	0.76	--	0.73
9	0.00	--	0.44	0.00	--	0.14	0.00	--	0.76
10	0.00	--	0.46	0.00	--	0.19	0.00	--	0.73
11	0.00	--	0.27	0.00	--	0.22	1.27	--	0.39
12	0.00	--	0.16	0.00	--	0.16	0.76	--	0.19
13	0.00	--	0.16	0.00	--	0.11	0.00	--	0.19
14	0.25	--	0.14	0.00	--	0.09	0.25	--	0.18
15	6.10	--	1.01	0.00	--	0.08	0.00	--	0.17
16	0.00	--	1.54	0.00	--	0.08	0.25	--	0.17
17	0.00	--	1.37	0.00	--	0.10	0.25	--	0.23
18	0.00	--	0.97	0.00	--	0.05	0.00	--	0.44
19	0.51	--	1.76	0.00	--	0.09	1.02	--	0.68
20	0.00	--	0.61	5.33	--	0.20	0.00	--	0.73
21	0.00	--	0.97	0.76	--	0.80	9.15	--	0.35
22	0.00	--	0.64	0.00	--	0.95	0.00	--	0.39
23	0.25	--	0.36	0.00	--	1.01	0.25	--	0.54
24	2.54	--	1.15	0.00	--	0.73	0.00	--	0.47
25	0.00	--	0.50	0.00	--	0.60	0.00	--	0.40
26	0.00	--	0.27	0.00	--	0.35	0.00	--	0.51
27	0.00	--	0.27	0.00	--	0.24	3.05	--	0.19
28	0.00	--	0.34	4.83	--	0.37	1.02	--	0.41
29	0.00	--	0.31	3.81	--	0.38	0.00	--	0.14
30	0.00	--	0.37	2.03	--	0.48	0.25	--	0.56
31				6.35	--	0.49			
TOT	9.65	--	17.61	23.11	--	9.20	26.15	--	14.20

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	December 1992			January 1993			February 1993		
Day	PRC# (mm)	BR (mm)	PM (mm)	PRC# (mm)	BR (mm)	PM (mm)	PRC# (mm)	BR (mm)	PM (mm)
1	0.00	--	0.63	TR	--	0.16	0.00	--	0.16
2	0.00	--	1.06	0.00	--	0.27	0.00	--	0.18
3	0.00	--	0.78	TR	--	0.19	0.00	--	0.18
4	0.00	--	0.25	1.27	--	0.16	0.00	--	0.49
5	0.00	--	0.23	TR	--	0.36	TR	--	0.64
6	0.00	--	0.23	0.00	--	0.34	TR	--	0.37
7	5.33	--	0.24	TR	--	0.26	0.00	--	0.64
8	1.78	--	0.12	1.52	--	0.17	0.00	--	0.61
9	0.00	--	0.59	3.30	--	0.34	0.51	--	0.45
10	6.10	--	0.21	TR	--	0.23	TR	--	0.42
11	0.00	--	0.31	TR	--	0.19	TR	--	0.34
12	0.00	--	0.29	TR	--	0.19	TR	--	0.52
13	0.00	--	0.18	0.00	--	0.25	0.00	--	0.62
14	0.00	--	0.48	2.03	--	0.19	0.00	--	0.99
15	0.00	--	0.77	0.00	--	0.15	0.00	--	0.86
16	1.02	--	0.38	1.02	--	0.13	0.00	--	0.75
17	0.76	--	0.32	TR	--	0.21	TR	--	0.77
18	0.00	--	0.17	TR	--	0.17	0.00	--	0.74
19	TR	--	0.16	1.27	--	0.14	8.38	--	0.23
20	TR	--	0.26	3.56	--	0.85	4.06	--	0.42
21	0.00	--	0.36	0.00	--	0.41	TR	--	0.32
22	0.00	--	0.53	0.25	--	0.62	0.00	--	0.41
23	0.00	--	0.49	TR	--	0.48	0.00	--	0.39
24	0.00	--	0.63	0.51	--	0.29	0.00	--	0.55
25	0.00	--	0.41	0.00	--	0.56	0.00	--	0.39
26	0.00	--	0.46	0.00	--	0.44	0.00	--	0.17
27	0.76	--	0.33	0.00	--	0.57	0.00	--	0.17
28	1.02	--	0.20	TR	--	0.43	0.00	--	0.35
29	0.51	--	0.21	TR	--	0.37			
30	2.54	--	0.09	TR	--	0.18			
31	3.05	--	0.13	1.02	--	0.15			
TOT	22.87	--	11.50	15.75	--	9.45	12.95	--	13.13

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	March 1993			April 1993			May 1993		
Day	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.00	--	0.22	2.03	--	1.15*	0.00	--	1.58
2	4.32	--	0.36	5.08	--	1.12	0.00	--	2.17
3	2.54	--	0.30	3.05	--	1.07	2.55	--	1.26
4	0.00	--	0.49	0.00	--	1.67	0.00	--	1.85
5	0.25	--	1.22	0.00	--	1.52	0.00	--	2.48
6	0.00	--	1.13	2.29	--	1.07	1.02	--	2.45
7	0.25	--	0.50	0.25	--	1.68	0.00	1.23	1.56
8	0.25	--	0.92	3.56	--	0.99	0.00	1.62	1.86
9	0.00	--	1.24	0.00	--	1.61	0.00	1.63	1.97
10	0.00	--	1.86	1.78	--	1.72	0.00	2.18	2.61
11	0.00	--	1.92	0.25	--	1.13	0.00	2.70	2.98
12	0.00	--	1.36	0.00	--	1.61	0.00	3.06	3.18
13	0.51	--	0.86	0.25	--	1.21	0.00	2.28	2.36
14	0.00	--	0.87	0.00	--	1.78	0.00	2.32	2.70
15	0.00	--	1.83	0.00	--	1.77	0.00	2.52	2.90
16	0.00	--	1.11	0.00	--	1.38	0.00	2.74	2.87
17	2.54	--	0.48	0.76	--	1.14	0.00	2.43	3.09
18	0.00	--	2.16	0.00	--	2.29	0.00	2.45	3.07
19	1.02	--	1.86	0.00	--	1.58	0.00	--	2.49
20	2.03	--	1.75	0.00	--	1.61	1.02	--	2.64
21	0.00	--	1.25	0.00	--	1.90	1.02	--	2.16
22	1.78	--	0.80	0.00	--	2.27	0.00	2.17	2.45
23	1.78	--	1.02	0.51	--	1.73	0.00	2.01	2.70
24	0.00	--	0.85	0.00	--	2.29	0.00	2.25	2.75
25	0.00	--	0.92	2.55	--	2.34	1.53	2.21	2.68
26	0.00	--	1.01	0.00	--	1.99	TR	2.93	3.16
27	0.00	--	1.08	0.00	--	2.15	0.00	1.48	1.63
28	0.00	--	1.33	0.00	--	1.33	0.25	1.22	1.67
29	0.00	--	1.02	0.76	--	2.15	0.00	2.07	2.40
30	0.00	--	0.76	0.00	--	2.38	3.82	1.90	2.03
31	0.00	--	0.63				4.08	2.55	2.57
TOT	17.27	--	33.11	23.12	--	49.63	15.29	--	74.27

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	June 1993			July 1993			August 1993		
Day	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.51	3.13	3.38	0.00	1.18	1.56	0.00	2.41	2.32
2	6.38	2.59	2.85	0.00	1.21	1.35	0.00	1.22	1.39
3	0.00	2.35	2.61	0.00	1.47	1.68	0.00	1.93	--
4	6.38	2.26	2.28	0.00	1.48	1.88	0.00	2.20	--
5	0.25	3.46	3.82	0.00	1.27	1.45	0.00	2.10	--
6	0.00	3.20	3.20	0.00	1.23	1.75	0.00	1.30	--
7	0.00	2.20	2.82	0.00	1.19	1.22	0.00	1.27	--
8	0.00	1.88	2.43	0.00	1.26	1.28*	0.00	1.55	--
9	1.02	2.13	2.40	0.00	1.00	1.38	0.00	1.20	--
10	0.00	2.21	2.72	0.00	2.36	2.07	0.00	0.96	--
11	3.06	2.30	2.65	0.00	1.65	1.71	0.00	1.65	--
12	0.00	2.40	2.93	0.00	0.84	0.93	0.00	1.17	--
13	0.00	2.09	2.51	3.57	1.92	1.97	0.00	0.79	--
14	0.00	1.71	1.71	0.00	1.65	1.81	0.00	0.74	0.72
15	0.00	1.70	2.38	TR	1.49	1.60	0.00	0.64	0.65
16	0.00	1.73	2.35	3.82	2.34	2.04	0.25	0.89	0.72
17	0.00	2.10	2.56	9.94	2.48	2.33	0.00	1.14	0.78
18	0.00	2.55	2.51	0.00	3.12	2.60	0.00	1.12	0.99
19	0.00	2.37	2.28	0.00	1.18	1.02	0.00	1.52	1.06
20	0.00	2.19	2.53	0.00	1.32	1.26	TR	0.62	--
21	TR	1.36	1.98	0.00	1.24	1.35	0.00	0.63	0.73
22	0.00	0.91	1.35	TR	1.68	1.88	0.00	1.16	0.65
23	0.00	1.12	1.57	0.00	1.25	1.16	0.00	0.78	0.92
24	0.00	1.40	1.48*	0.00	0.55	0.64	0.00	0.78	--
25	0.00	1.75	1.94*	8.92	2.43	2.57	0.00	0.91	--
26	0.00	1.72	1.58*	0.00	2.63	2.35	0.00	0.83	--
27	0.00	0.86	1.34	0.00	2.68	2.65	0.00	0.53	--
28	0.00	1.06	1.70	5.10	1.74	2.14	0.00	0.56	--
29	0.00	1.07	1.28	1.02	2.67	2.90	0.00	0.65	--
30	0.00	1.15	1.62	0.00	1.52	1.55	0.00	0.38	--
31				0.00	2.35	1.91	0.00	0.48	--
TOT	17.60	58.95	68.76	32.37	52.38	53.99	0.25	34.11	--

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	September 1993			October 1993			November 1993		
Day	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.00	0.42	--	0.00	0.22	--	0.00	--	0.24
2	0.00	0.51	--	0.00	0.16	--	0.00	--	0.09
3	0.00	0.33	--	0.00	0.15	--	0.25	--	0.18
4	0.00	0.32	--	0.00	0.12	--	0.00	--	0.15
5	0.00	0.27	--	0.00	0.17	--	0.00	--	0.22
6	0.00	0.28	--	0.00	0.10	--	0.00	--	0.25
7	0.00	0.28	--	0.00	0.18	--	0.00	--	0.21
8	0.00	0.36	--	0.00	0.41	--	0.00	--	0.28
9	0.00	0.24	--	0.00	0.65	--	0.00	--	0.28
10	0.00	0.33	--	0.00	0.36	--	0.00	--	0.25
11	0.00	0.32	--	0.00	0.50	--	0.00	--	0.21
12	0.00	0.25	--	0.00	0.59	--	0.00	--	0.22
13	0.00	0.22	--	TR	0.76	--	0.76	--	0.41
14	4.85	0.72	0.67	TR	0.41	--	0.00	--	0.13
15	0.00	1.07	1.19	1.27	0.61	--	0.00	--	0.21
16	0.00	0.71	1.39	0.51	0.56	--	0.00	--	0.16
17	0.00	0.49	0.38	0.00	1.22	--	0.51	--	0.16
18	0.00	0.40	0.37	0.00	0.83	--	0.25	--	0.40
19	0.00	0.29	0.46	0.00	0.55	--	0.00	--	0.21
20	0.00	0.22	0.38	0.00	0.80	--	0.00	--	0.14
21	0.00	0.29	0.27	0.00	0.35	--	0.00	--	0.21
22	0.00	0.27	0.27	0.00	0.62	--	TR	--	0.34
23	0.00	0.31	0.39	0.00	0.16	--	0.00	--	0.11
24	TR	0.25	0.35	0.00	0.40	--	0.00	--	0.09
25	0.00	0.21	--	0.00	0.65	--	0.00	--	0.09
26	0.00	0.23	--	0.00	0.55	--	0.00	--	0.16
27	0.00	0.17	--	0.00	0.03	--	0.00	--	0.19
28	0.00	0.22	--	0.00	0.17	--	0.00	--	0.12
29	0.00	0.18	--	0.00	0.46	--	0.51	--	0.04
30	0.00	0.25	--	0.00	0.36	--	3.05	--	0.11
31				0.00	0.32	--			
TOT	4.85	10.41	--	1.78	13.42	--	5.33	--	5.86

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	December 1993			January 1994			February 1994		
Day	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	2.79	--	0.01	2.79	--	0.27	0.00	--	0.58
2	2.54	--	0.18	2.79	--	0.13	0.00	--	0.25
3	0.00	--	0.08	3.81	--	0.09	0.00	--	0.33
4	0.00	--	0.68	0.51	--	0.11	0.00	--	0.25
5	0.00	--	0.25	0.00	--	0.22	0.00	--	0.28
6	0.00	--	0.16	0.00	--	0.40	0.00	--	0.29
7	3.30	--	0.03	0.00	--	0.04	0.00	--	0.52
8	7.37	--	0.16	1.27	--	0.20	0.00	--	0.34
9	1.02	--	0.00	0.00	--	0.57	0.00	--	0.59
10	1.02	--	0.00	0.00	--	0.05	0.00	--	0.34
11	0.00	--	0.26	0.00	--	0.45	0.00	--	0.54
12	0.00	--	0.31	0.00	--	0.30*	0.00	--	0.35
13	1.78	--	0.19	0.00	--	0.58	0.00	--	0.67
14	1.27	--	0.40	0.00	--	0.43	0.00	--	0.45
15	0.00	--	0.22	0.00	--	0.52	0.00	--	0.40
16	0.00	--	0.17	0.00	--	0.61	0.00	--	0.20
17	0.00	--	0.17	0.00	--	0.25	8.89	--	0.53
18	0.00	--	0.16	0.00	--	0.53	0.00	--	1.10
19	0.00	--	0.18	0.00	--	0.67	0.00	--	0.73
20	0.00	--	0.21	0.25	--	0.57	0.00	--	0.47
21	0.00	--	0.45	0.00	--	0.35	0.00	--	0.71
22	0.00	--	0.06	1.52	--	0.42	0.00	--	0.77
23	0.00	--	0.25	0.51	--	0.24	0.25	--	0.61
24	0.00	--	0.19	0.51	--	0.38	0.25	--	0.25
25	0.00	--	0.16	0.00	--	0.35	0.51	--	0.35
26	0.00	--	0.13	0.00	--	0.66	1.27	--	0.28
27	0.00	--	0.12	0.00	--	0.60	0.25	--	0.65
28	0.00	--	0.11	0.00	--	0.39	0.25	--	0.61
29	0.00	--	0.10	0.00	--	0.41			
30	0.00	--	0.06	0.00	--	0.40			
31	7.87	--	0.15	0.00	--	0.51			
TOT	28.96	--	5.60	13.96	--	11.70	11.67	--	13.44

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	March 1994			April 1994			May 1994		
Day	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.00	--	0.23	0.00	--	0.55	0.00	--	0.92
2	0.00	--	0.22	TR	--	0.58	0.00	--	1.23
3	0.00	--	0.79	TR	--	0.69	0.00	--	0.82
4	0.00	--	1.05	0.00	--	0.86	3.30	--	1.50
5	0.00	--	0.99	2.03	--	0.85	0.25	--	2.07
6	0.00	--	0.77	0.00	--	1.56	0.00	2.29	2.07
7	0.00	--	0.66	0.00	--	0.84	0.00	2.49	1.78
8	0.00	--	0.71	11.73	--	0.94	0.00	2.21	1.93
9	0.00	--	0.50	0.00	--	1.88	0.00	2.21	2.16
10	0.00	--	0.64	0.00	--	1.68	0.00	1.66	0.79
11	0.00	--	0.60	0.00	--	1.32	TR	1.16	1.30
12	0.00	--	0.54	0.00	--	1.11	0.00	2.44	0.53
13	0.00	--	0.42	0.00	--	0.92	0.00	1.32	1.10
14	0.00	--	0.76	0.00	--	0.90	0.00	1.70	0.94
15	0.00	--	0.81	0.00	--	1.29	12.95	1.61	1.30
16	0.00	--	0.69	0.00	--	1.10	0.00	3.95	2.67
17	0.00	--	0.45	0.00	--	1.24	0.00	2.27	1.59
18	0.51	--	0.94	0.00	--	1.05	0.25	1.43	1.31
19	0.00	--	0.63	5.84	--	1.79	3.56	1.79	1.75
20	0.76	--	0.48	0.00	--	1.76	1.78	--	2.74
21	0.25	--	0.91	1.52	--	1.62	0.00	--	2.01
22	0.00	--	0.62	0.00	--	0.96	0.00	--	1.68
23	0.00	--	0.55	0.00	--	1.07	0.00	--	1.93
24	0.00	--	0.38	0.00	--	1.14	0.00	--	1.50*
25	0.00	--	0.53	1.27	--	1.18	0.00	--	2.05
26	0.00	--	0.77	0.00	--	0.95	0.00	--	0.68*
27	0.00	--	0.53	0.00	--	0.95	0.00	--	0.94*
28	0.00	--	0.78	0.00	--	0.98	0.00	--	0.54
29	0.00	--	0.74	0.00	--	1.01	0.00	--	0.49*
30	TR	--	0.36	0.00	--	1.09	0.00	--	0.76*
31	0.00	--	0.31				0.25	1.11	1.08
TOT	1.52	--	19.36	22.39	--	33.86	22.34	--	44.16

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

Day	June 1994			July 1994			August 1994		
	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.00	--	0.57	0.00	--	0.23*	0.00	--	0.29*
2	0.00	--	0.34	0.00	0.22*	0.28*	0.00	--	0.25*
3	TR	--	1.69	0.00	0.29*	0.26*	0.00	--	0.24*
4	0.00	--	0.96	0.00	0.28*	0.25*	0.00	--	0.35*
5	1.02	--	0.33	TR	0.48*	0.18*	0.00	--	0.36*
6	1.02	--	1.13	0.00	0.44*	0.24*	0.00	--	0.33*
7	0.00	--	1.11	0.00	0.41*	0.22*	1.46	--	0.33*
8	0.00	--	0.86	0.00	0.27*	0.22*	TR	--	1.19*
9	0.00	--	0.59	0.00	0.22*	0.23*	0.00	--	0.72*
10	0.00	--	1.08	0.00	0.17*	0.22*	0.00	--	0.51*
11	0.00	--	0.47	0.00	--	0.22*	0.00	--	0.31*
12	1.27	--	1.66	0.00	--	0.21*	0.00	--	0.25*
13	3.05	--	2.64	0.00	--	0.21*	0.00	--	0.21*
14	0.00	--	1.54	0.00	--	0.23*	0.00	--	0.18*
15	0.00	--	1.06	0.00	--	0.21*	0.00	--	0.22*
16	0.00	--	0.49	0.00	--	0.23*	0.00	--	0.19*
17	0.00	--	0.57	0.00	--	0.23*	0.00	--	0.27*
18	3.30	--	2.20	0.00	0.26*	0.27*	0.00	--	0.14*
19	0.00	--	0.65	0.00	0.31*	0.25*	0.00	--	0.18*
20	0.00	--	0.66*	0.00	0.26*	0.24*	0.00	--	0.15*
21	0.00	--	0.65*	0.00	0.24*	0.23*	0.00	--	0.12*
22	0.25	--	0.42*	0.00	--	0.21*	0.00	--	0.18*
23	0.00	--	0.57*	0.00	--	0.18*	0.00	--	0.14*
24	0.00	--	0.42*	0.00	--	0.22*	0.00	--	0.15*
25	0.00	--	0.37*	0.00	--	0.26*	0.00	--	0.23*
26	0.00	--	0.35*	0.00	--	0.26*	0.51	--	0.78*
27	0.00	--	0.33*	0.00	--	0.25*	0.00	--	0.16*
28	0.00	0.37*	0.31*	0.00	--	0.28	TR	--	0.17*
29	0.00	0.36*	0.31*	0.00	--	0.29*	0.00	--	0.12*
30	0.00	0.25*	0.28*	0.00	--	0.34*	0.00	--	0.10*
31				0.00	--	0.33	0.00	--	0.11*
TOT	9.91	--	24.61*	0.00	--	7.48*	1.97	--	8.93*

Table 2.--*Daily and monthly precipitation and evapotranspiration at Black Rock Valley site, March 27, 1992, to October 31, 1994--Continued*

	September 1994			October 1994		
Day	PRC (mm)	BR (mm)	FX (mm)	PRC (mm)	BR (mm)	FX (mm)
1	0.00	--	0.10*	0.00	--	0.07*
2	0.51	--	0.13*	0.00	--	0.08*
3	0.76	--	1.83*	0.00	--	0.08*
4	0.00	--	0.45*	0.00	--	0.08*
5	0.00	--	0.14*	0.00	--	0.07*
6	0.00	--	0.10*	0.00	--	0.07*
7	0.00	--	0.09*	0.00	--	0.07*
8	0.00	--	0.10*	0.00	--	0.06*
9	0.00	--	0.10*	0.00	--	0.06*
10	0.00	--	0.10*	0.00	--	0.04*
11	TR	--	0.04*	0.00	--	0.03*
12	0.00	--	0.06*	0.00	--	0.05*
13	0.00	--	0.04*	6.86	--	0.34*
14	0.76	--	0.72*	3.05	--	1.27*
15	0.00	--	0.15*	0.00	--	0.29*
16	0.00	--	0.12*	0.00	--	0.23*
17	0.00	--	0.06*	0.00	--	0.21*
18	0.00	--	0.06*	0.00	--	0.22*
19	0.00	--	0.05*	0.00	--	0.13*
20	0.00	--	0.08*	0.00	--	0.08*
21	0.00	--	0.09*	0.00	--	0.12*
22	0.00	--	0.08*	0.00	--	0.07*
23	0.00	--	0.08*	0.00	--	0.08*
24	0.00	--	0.08*	0.00	--	0.09*
25	0.00	--	0.07*	0.00	--	0.20
26	0.00	--	0.07*	9.40	--	0.40
27	0.00	--	0.07*	23.37	--	0.64
28	0.00	--	0.06*	0.00	--	1.23
29	0.25	--	0.28*	0.00	--	0.62
30	0.00	--	0.08*	0.00	--	0.50
31				11.43	0.81*	1.18
TOT	2.28	--	5.48*	54.11	--	8.66*

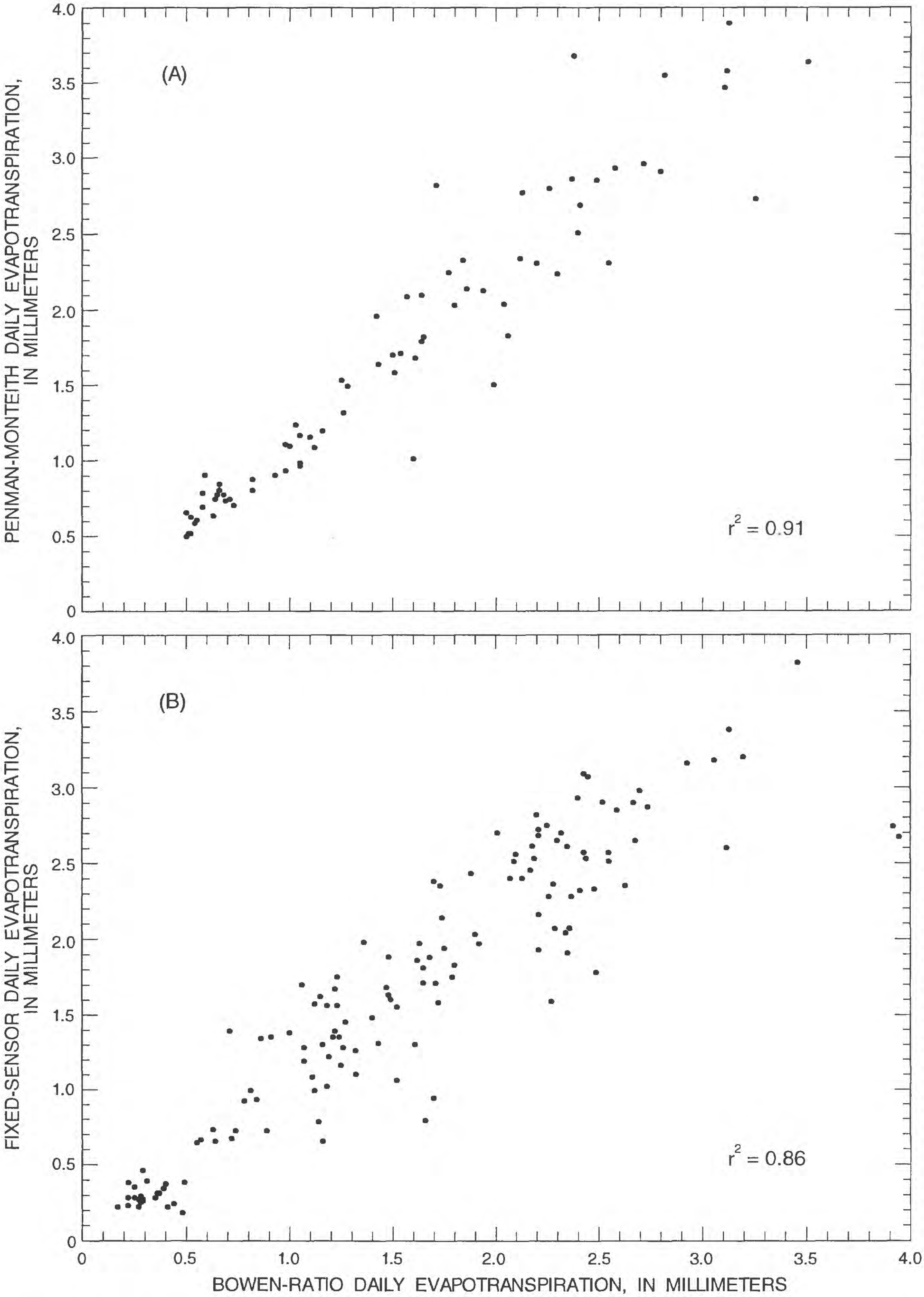


Figure 19.--Bowen-ratio and Penman-Monteith daily evapotranspiration (A) and Bowen-ratio and fixed-sensor daily evapotranspiration (B) at Black Rock Valley site.

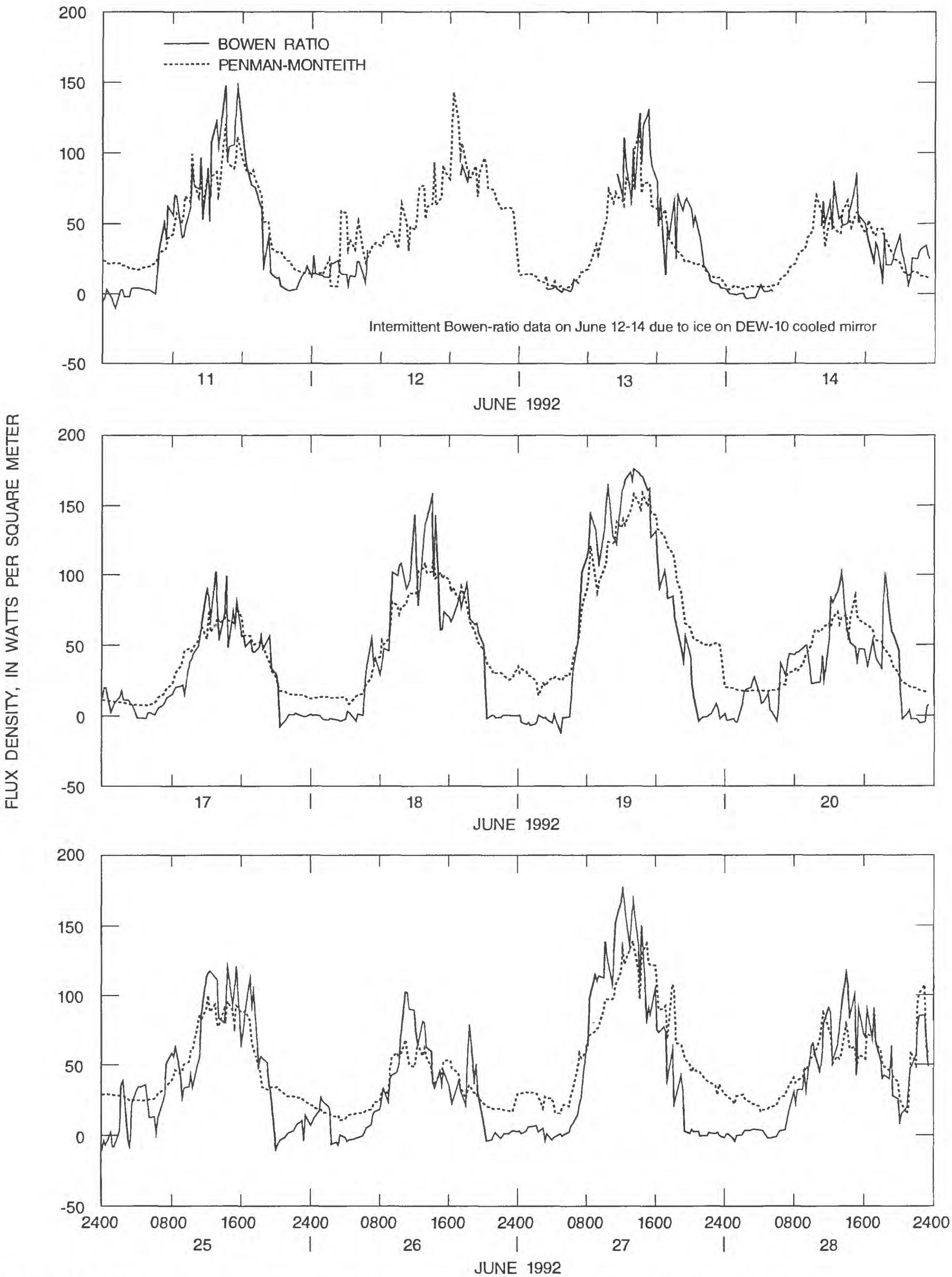


Figure 20.--Bowen-ratio and Penman-Monteith latent-heat flux at Black Rock Valley site, June 11-14, 17-20, and 25-28, 1992.

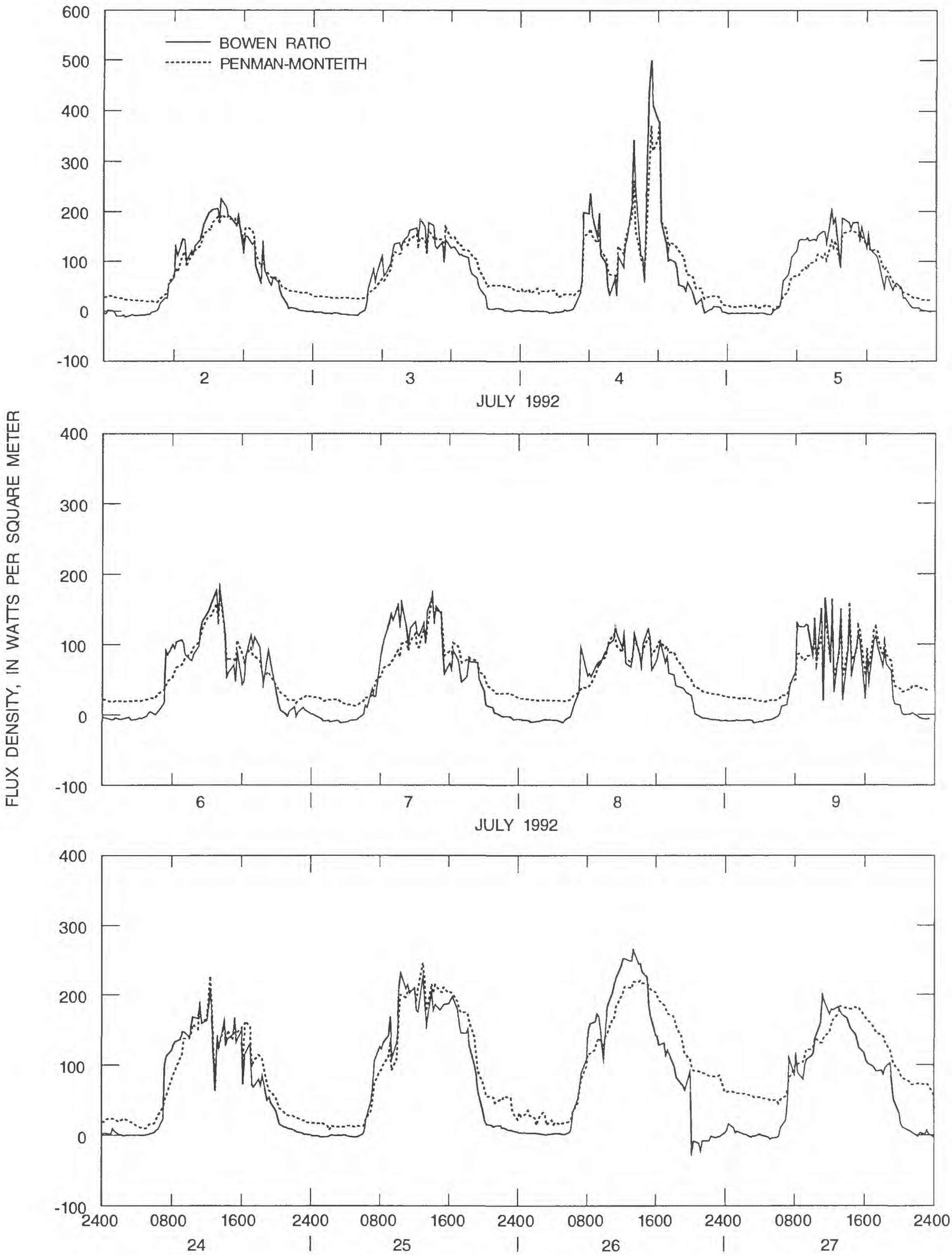


Figure 21.--Bowen-ratio and Penman-Monteith latent-heat flux at Black Rock Valley site, July 2-9, and July 24-27, 1992.

However, during nights with winds of 6-9 m/s, Bowen-ratio and Penman-Monteith latent-heat flux and ET did not agree well. For example, from July 26-27, 1992, Penman-Monteith latent-heat flux and ET averaged about 40 percent higher than Bowen-ratio ET (fig. 21; table 2). During other periods, such as June 18-19 and 26-28, 1992, the differences in latent-heat flux and ET were less (fig. 20; table 2), but still noticeable at night. During the summer, the Black Rock Valley, Bird Canyon, and Firewater Canyon sites are subject to diurnal wind patterns because of their location. Upslope winds of 1 to 3 m/s prevailed during the day, while downslope winds of 6 to 9 m/s sometimes occurred at night (fig. 22). The higher wind speeds at night were probably due to the channeling effect of the topography around the sites. The Penman-Monteith method seems to be more sensitive to high wind speeds at night than the Bowen-ratio method, though both methods take turbulent theory into account.

Possibly some of the differences between the results from the Bowen-ratio and Penman-Monteith methods may be attributed to the methods. The Bowen-ratio method sometimes does not provide accurate results at night, when the Bowen ratio approaches or equals -1, which produces unreasonably large positive or negative latent-heat fluxes. However, time steps when the Bowen ratio approached or equalled -1 were not included in the analyses; they were replaced with the average of Bowen ratios from adjacent time steps. Also, using the daytime average canopy resistances (determined using the Bowen-ratio method) at night in the Penman-Monteith method may have contributed to higher Penman-Monteith ET at night compared with the Bowen-ratio ET. Used as a calibration factor, canopy resistances may be different at night than during the day, but low net radiation and soil-heat flux at night usually make latent-heat flux and ET near zero, regardless of the canopy resistance used—the exception appears to be during periods of high winds. The effects of the methods in these results is not quantifiable because a third, independent method was not used at the sites. However, the pattern of high ET associated with high wind speeds at night, determined by the same Bowen-ratio/Penman-Monteith method combination, was supported by data from weighing lysimeters at the ALE Reserve (Tomlinson, 1995, p. 52-53; Tomlinson, 1996a). In these instances, high ET at night was observed with the Penman-Monteith method and the weighing lysimeters, but not with the Bowen-ratio method.

Comparison of Latent-Heat Flux and Evapotranspiration from Bowen-Ratio and Fixed-Sensor Instruments

Fixed-sensor instruments produced reasonable estimates of latent-heat flux and ET, compared with fine-wire thermocouple/cooled-mirror hygrometer Bowen-ratio instruments, for a number of environmental conditions such as clouds, rain, high wind (wind speed greater than 3 m/s), and cool air temperatures (temperatures less than 20°C) (figs. 23-30). At the Black Rock Valley site for days in 1993 and 1994 when both systems were used, ET estimated with fixed-sensor instruments averaged 4.3 percent more than ET estimated with Bowen-ratio instruments (table 2). The r^2 on the daily values was 0.86 (fig 19). The r^2 is lower than that for the Bowen-ratio and Penman-Monteith ET comparison probably because the Bowen-ratio and fixed-sensor instrument systems were completely independent while the Penman-Monteith results were dependent on results from the Bowen-ratio instruments to estimate canopy resistance. However, there were some periods when the latent-heat flux and ET from the Bowen-ratio and fixed-sensor instruments agreed very closely, such as May 30 to June 6, 1993 ($r^2 = 0.94$; figs. 23-24; table 2). At the Black Rock Valley site, latent-heat fluxes estimated with fixed-sensor instruments matched latent-heat fluxes estimated with Bowen-ratio instruments most closely on partly cloudy or cloudy, rainy, and windy days, such as May 30 to June 6, 1993 (figs. 23-24), June 9-16, 1993 (figs. 24-25), and July 13-18, 1993 (fig. 26). During cloudy, windy, or rainy periods, perhaps sensor bias was small, which resulted in the good agreement. In these cases, radiation-induced errors in the measured profiles of air temperature and vapor pressure were most likely diminished, and wind provided ventilation for the air-temperature sensors (W. Bidlake, U.S. Geological Survey, written commun., 1996). Fixed-sensor instruments also produced similar favorable agreement with the Bowen-ratio instruments at the Bird Canyon and Firewater Canyon sites in 1995 (figs. 29-30). Regularly replacing the RH-207 relative-humidity chips was key in maintaining a close agreement between the Bowen-ratio and fixed-sensor latent-heat fluxes. In this study, the chips were replaced every 6-9 months.

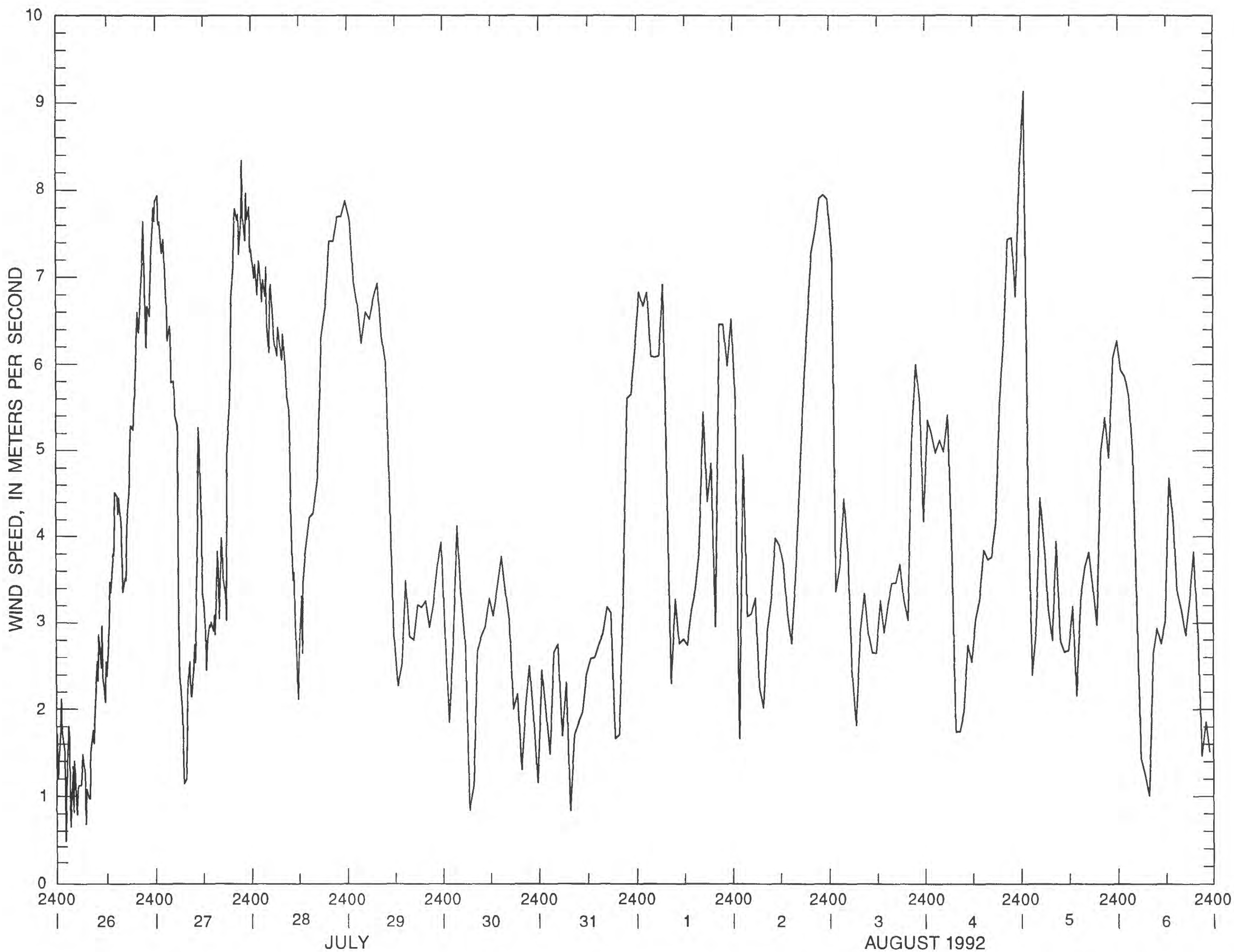


Figure 22.--Wind speed at 3.0 meters above the canopy at Black Rock Valley site, July 26 to August 6, 1992.

Clear days provided different comparisons between latent-heat flux and ET estimated with Bowen-ratio and fixed-sensor instruments. On some clear days, such as May 26 and 29, 1993 (fig. 23) and June 19 and 24, 1993 (fig. 25), latent heat fluxes estimated with Bowen-ratio and fixed-sensor instruments matched fairly well. On other clear days, such as May 24, 1993 (fig. 23), June 17, 1993 (fig. 25), and July 28, 1993 (fig. 27), agreement was still close, but somewhat less satisfactory than other periods. On clear days later in summer, such as August 8-10 and 12-13, 1993 (figs. 27-28), agreements were occasionally unsatisfactory. In these cases, the fixed-sensor instruments often showed negative (and probably inaccurate) vapor-pressure gradients, resulting in negative latent-heat fluxes, while the Bowen-ratio instruments showed positive gradients and positive latent-heat fluxes, which is what would be expected on clear, sunny days. Apparently when air and soil-moisture conditions become extremely dry, as they often do at the study sites in late summer and early fall, sensor error for the fixed sensors is perhaps higher than in cloudier, wetter conditions, resulting in the negative fluxes.

In 1994, a very dry year at the Black Rock Valley site, conditions in summer became so dry that neither Bowen-ratio nor fixed-sensor instruments were able to consistently measure accurate vapor-pressure gradients in summer or fall (table 2). In these cases, a Bowen ratio had to be estimated or partly estimated from June 20 to October 24, 1994 using data believed to be representative of true conditions. Each day, selected 20-minute intervals of data believed to represent true conditions were used to estimate a daily average Bowen ratio. These intervals were those that provided small, positive values of latent-heat flux, which is what would be expected. Intervals of data which produced negative latent-heat fluxes were not used. Some days on figure 31 show the intervals used clearly. For example, daytime intervals on August 18, 25-27, and 31 (fig. 31) where the DEW-10 Bowen ratio intersects with the estimated Bowen-ratio were those used to figure an estimated Bowen ratio. The selected intervals were summed, then divided by the number of intervals for the day, to determine an average daily Bowen ratio. This average daily Bowen-ratio was used to partition the available energy into latent- and sensible-heat flux for all 20-minute intervals of that day. This procedure produced reasonable, positive estimates of latent-heat flux and ET, rather than the unreasonable, negative estimates that would have resulted (fig. 31). Because soil moisture ranged from 2 to 4 percent and only very light amounts of precipitation fell from June 20 to October 24, ET would have been very low also, generally less than 0.3 mm/day (near the precision limits of the Bowen-ratio instruments), except after the light rainfalls. During periods of light rainfall such as August 26 and September 3, 1994, the Bowen- ratio DEW-10 measured positive vapor-pressure gradients for part or most of the day allowing fairly good estimates of ET for those periods (fig. 31). Daily ET was estimated at less than 0.3 mm for 80 percent of the June 20 to October 24 period, consistent with results obtained at the grass and sage lysimeter sites on the ALE Reserve (Tomlinson, 1996b), about 40 km east of the Black Rock Valley site. Possible reasons for the negative vapor-pressure gradients (and resultant negative latent-heat fluxes) are (1) vapor-pressure gradients too small for the cooled-mirror hygrometer to measure; (2) advection of air from another area, such as the field at the Bird Canyon site, which might affect the airstream reaching the upper air sensors; and (3) very dry soils absorbing moisture from the air (C. Fristchen, Radiation and Energy Balance Systems, oral commun., 1994). Other researchers have noted negative gradients when the cooled-mirror hygrometer was subject to a combination of high air temperatures and relative humidities of 9% or lower (M.J. Johnson and W.D. Nichols, U.S. Geological Survey, oral commun., 1995). Negative gradients have been observed with other Bowen-ratio instruments under very dry conditions (C. Fritschen, Radiation and Energy Balance Systems, written commun., 1994). In addition, negative gradients have been observed with the cooled-mirror hygrometer in other circumstances as well as dry conditions (Tomlinson, 1995, p. 63-64; Tomlinson, 1996a), including periods when the eddy-correlation method showed positive gradients (Tomlinson, 1996b).

In summary, under many environmental conditions, the fixed-sensor instruments provided reasonable estimates of latent-heat flux and ET, compared with estimates from the Bowen-ratio instruments. Bowen-ratio and fixed-sensor latent-heat fluxes consistently disagreed only under conditions of warm air temperatures combined with clear skies, dry soil, and dry atmosphere. The close correlation between the two systems allowed Bowen-ratio estimates of ET to be made during periods when the cooled- mirror hygrometer malfunctioned or could not be used, such as in freezing winter weather. During extremely dry periods in 1994, sensors used in both systems provided unreasonable estimates of latent-heat flux and ET, and daily ET estimates had to be made using average Bowen ratios based on selected 20-minute intervals of data believed to represent actual conditions. (Text continued on p. 58.)

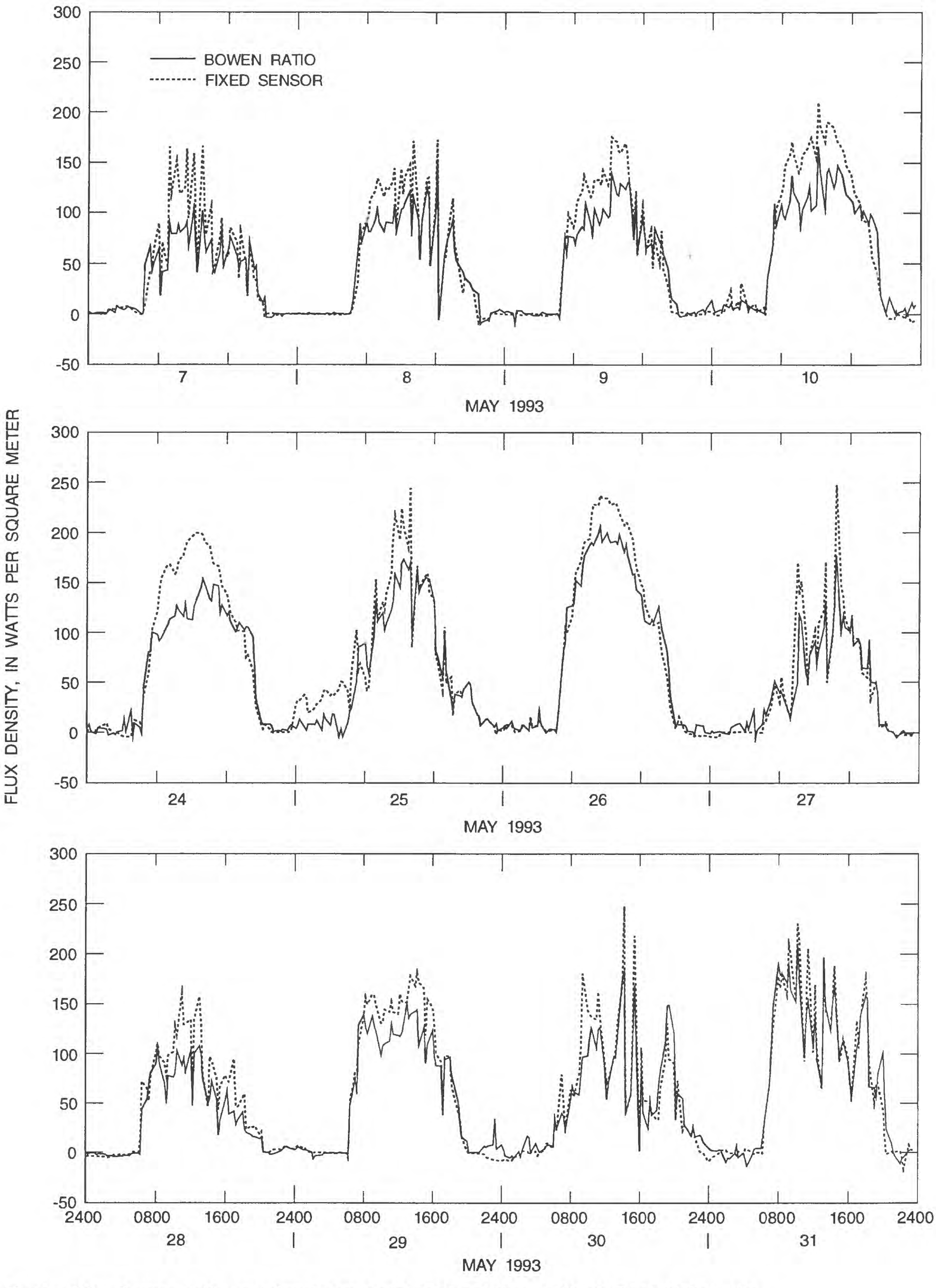


Figure 23.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, May 7-10, and May 24-31, 1993.

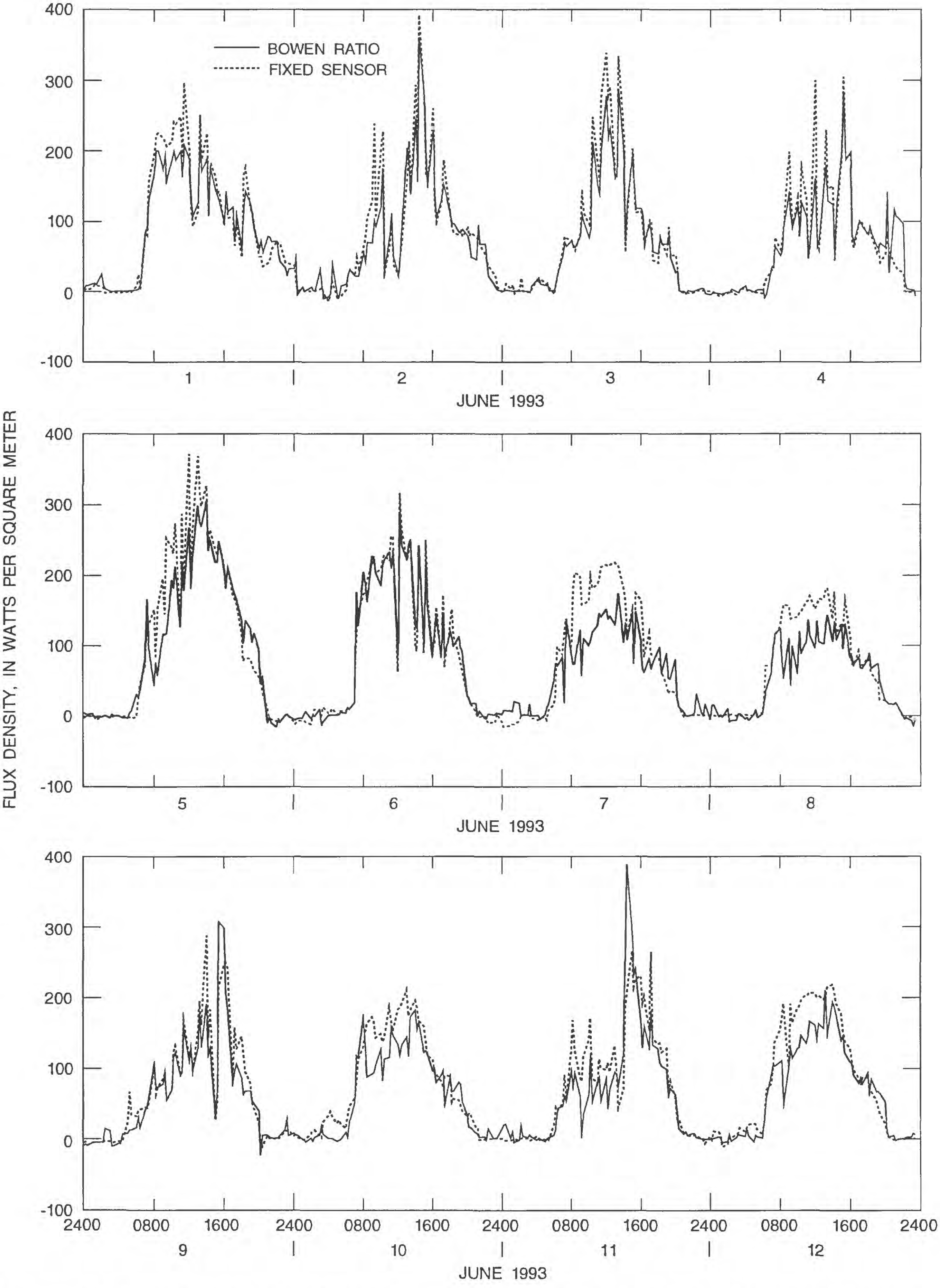


Figure 24.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, June 1-12, 1993.

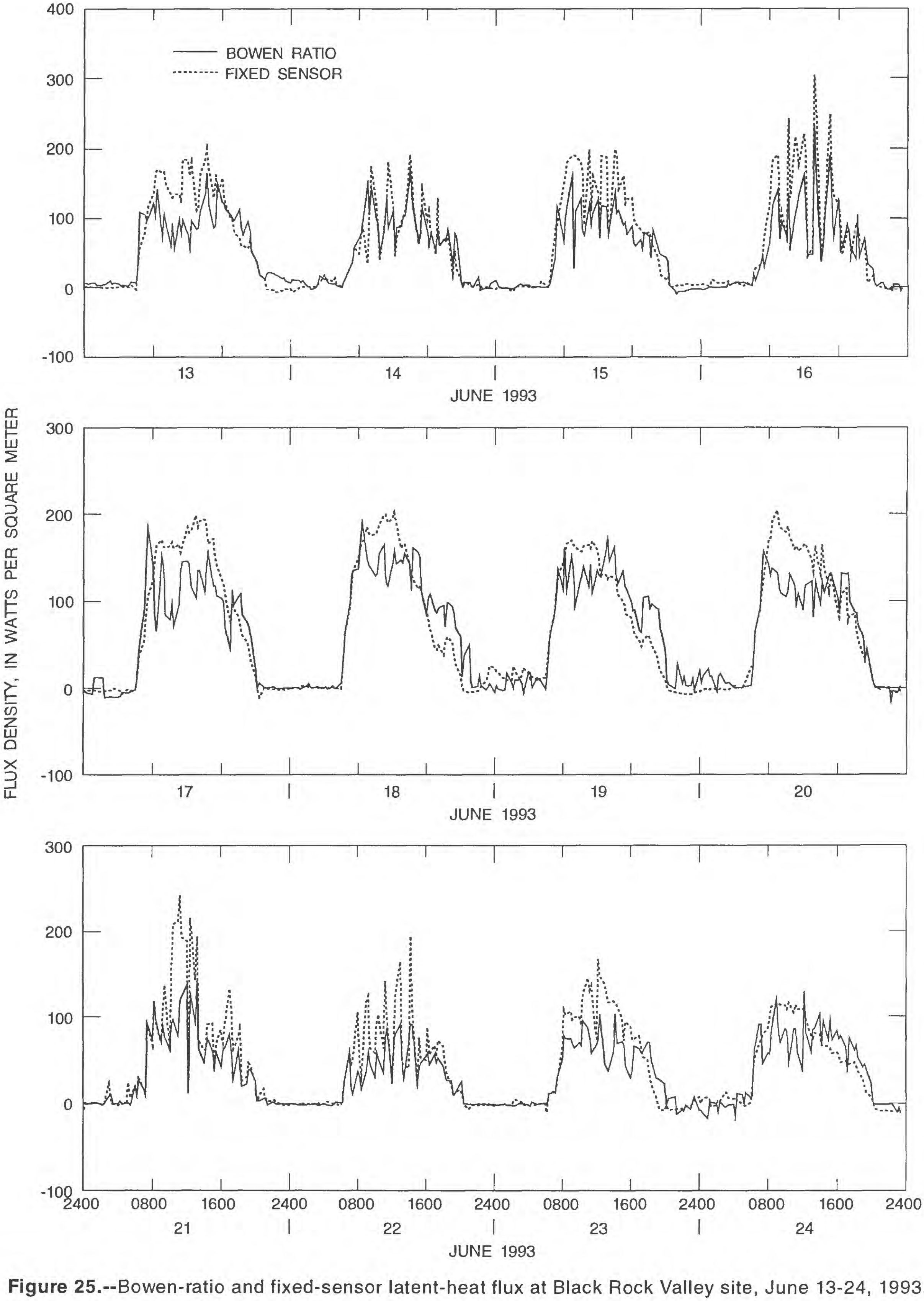


Figure 25.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, June 13-24, 1993.

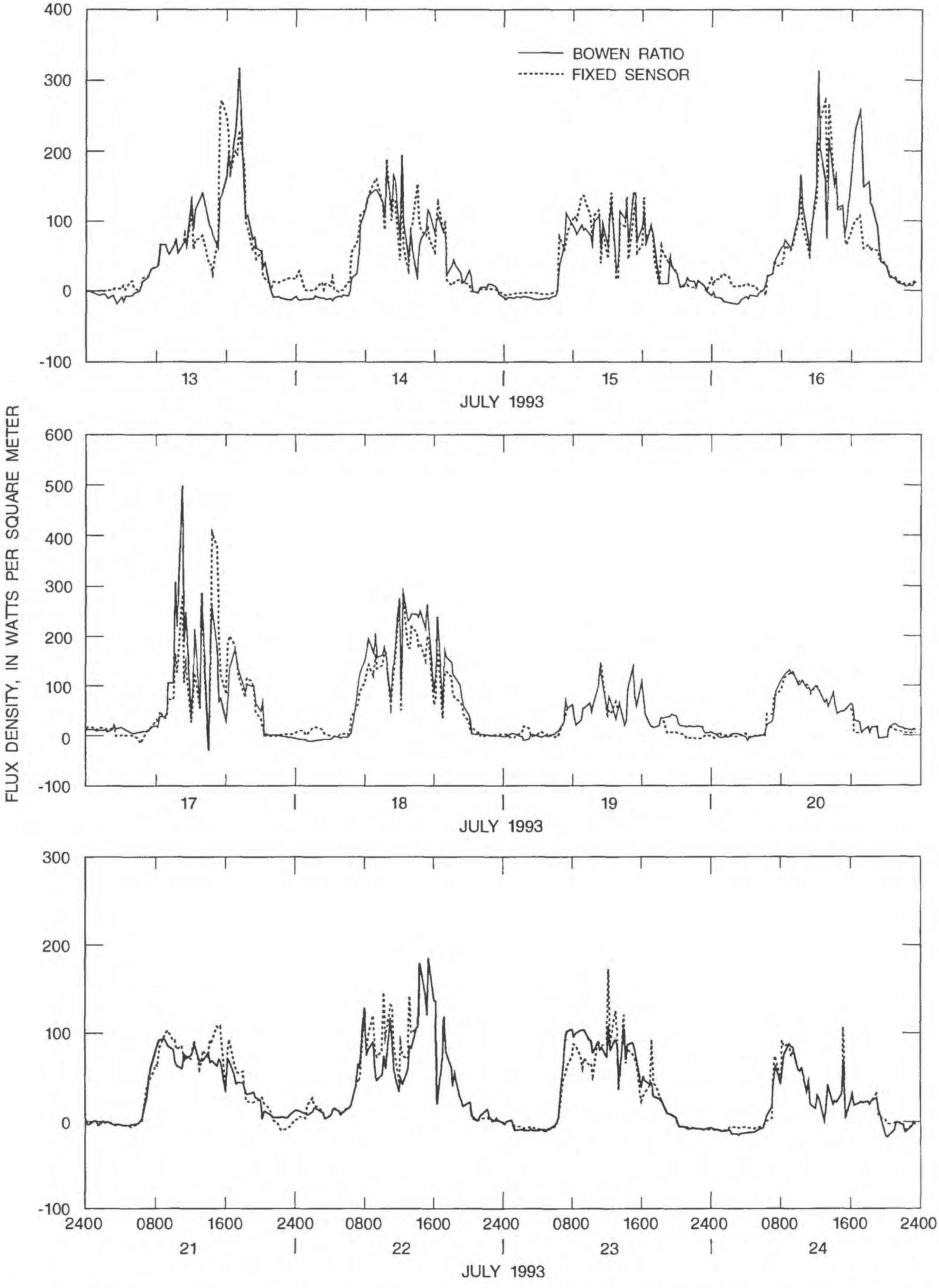


Figure 26.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, July 13-24, 1993.

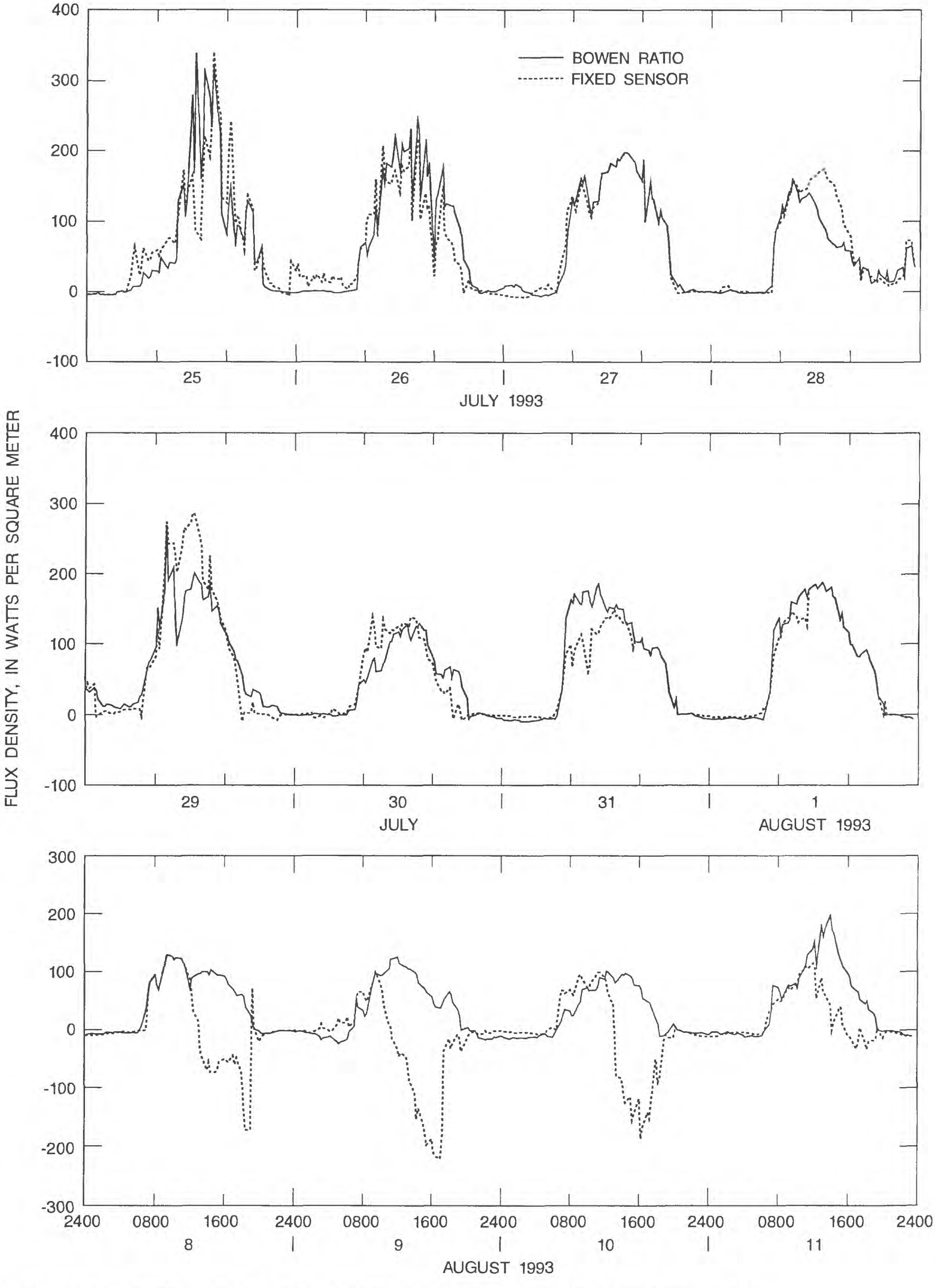


Figure 27.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, July 25 to August 1, and August 8-11, 1993.

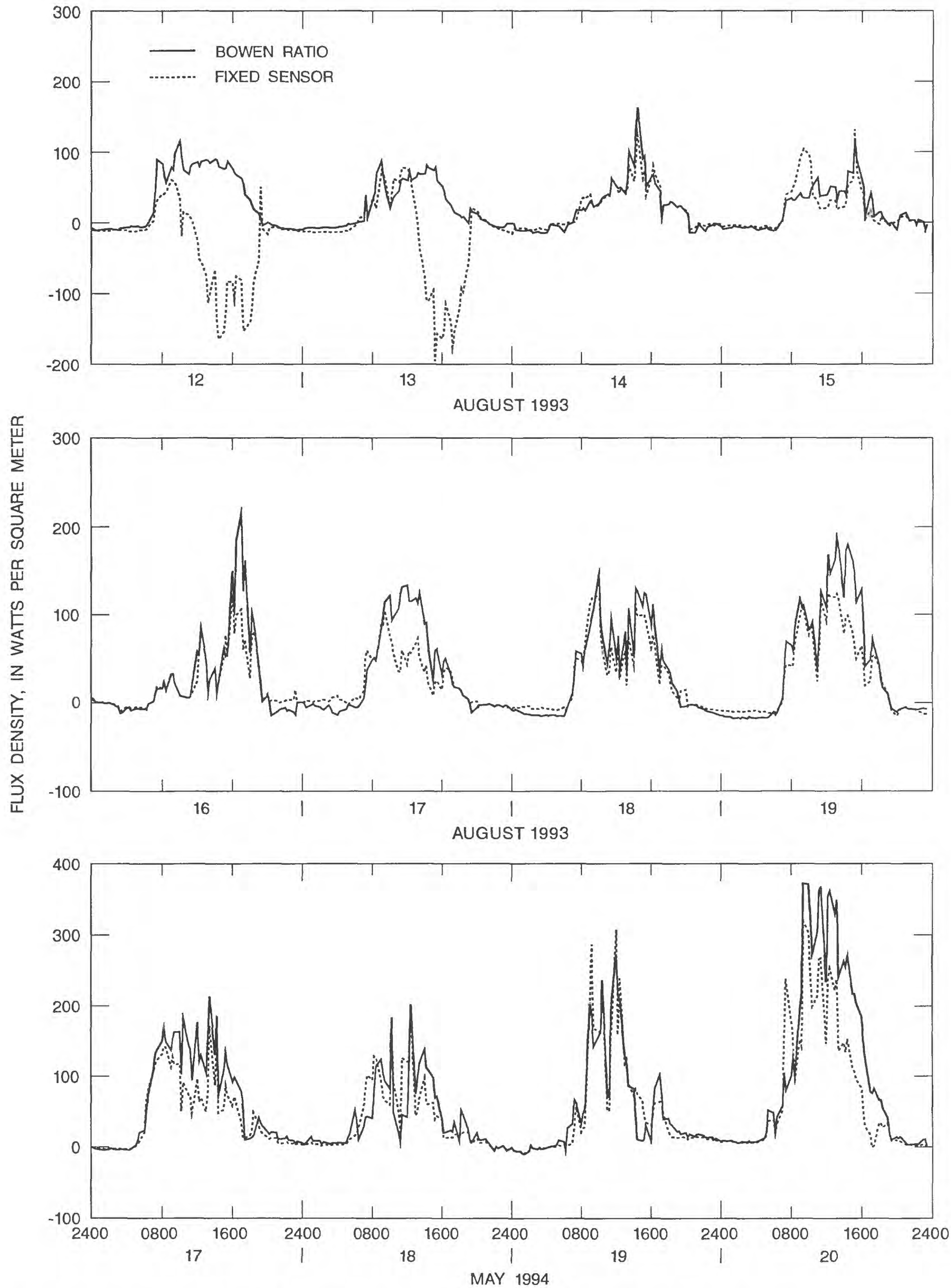


Figure 28.--Bowen-ratio and fixed-sensor latent-heat flux at Black Rock Valley site, August 12-19, 1993, and May 17-20, 1994.

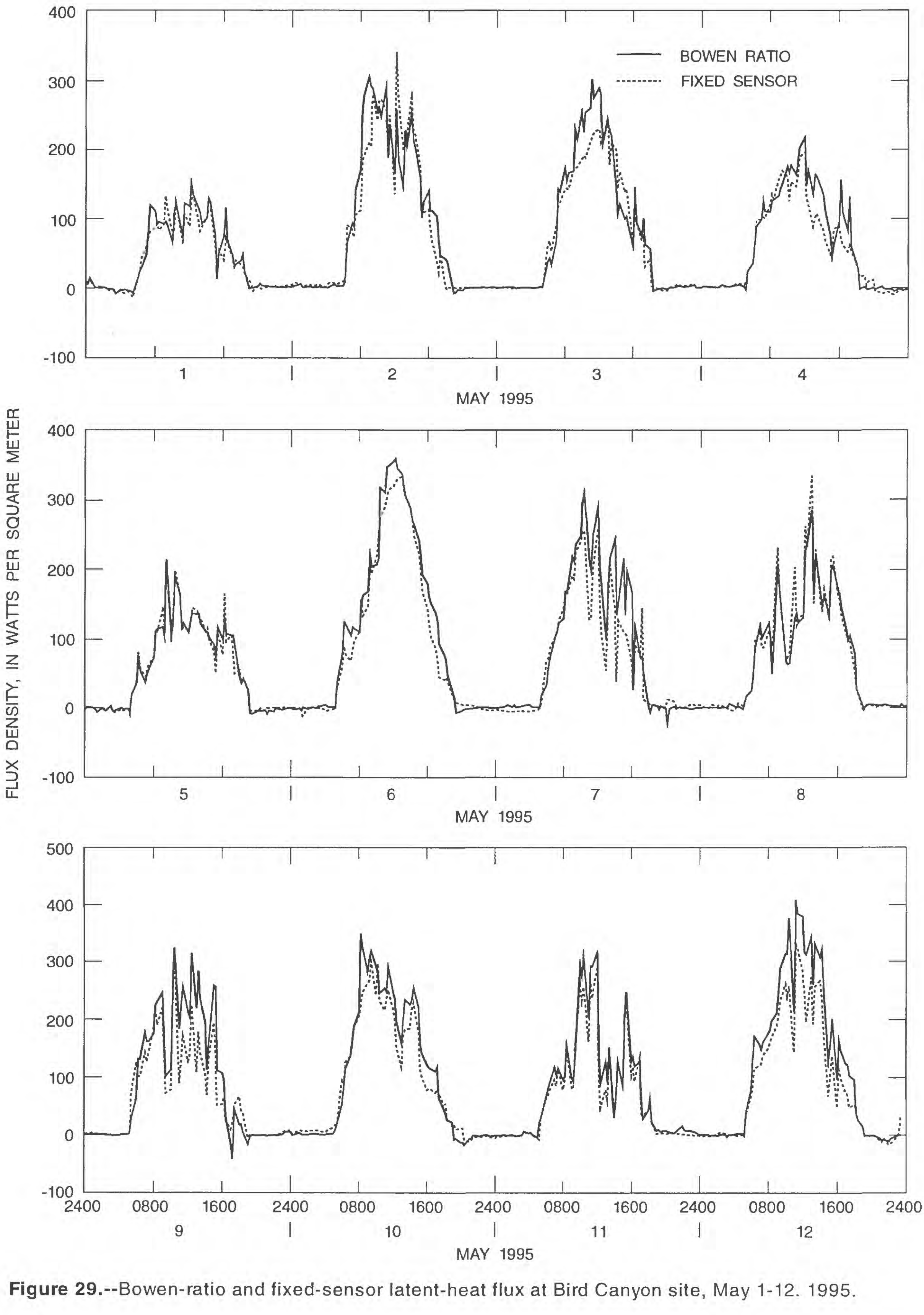


Figure 29.--Bowen-ratio and fixed-sensor latent-heat flux at Bird Canyon site, May 1-12. 1995.

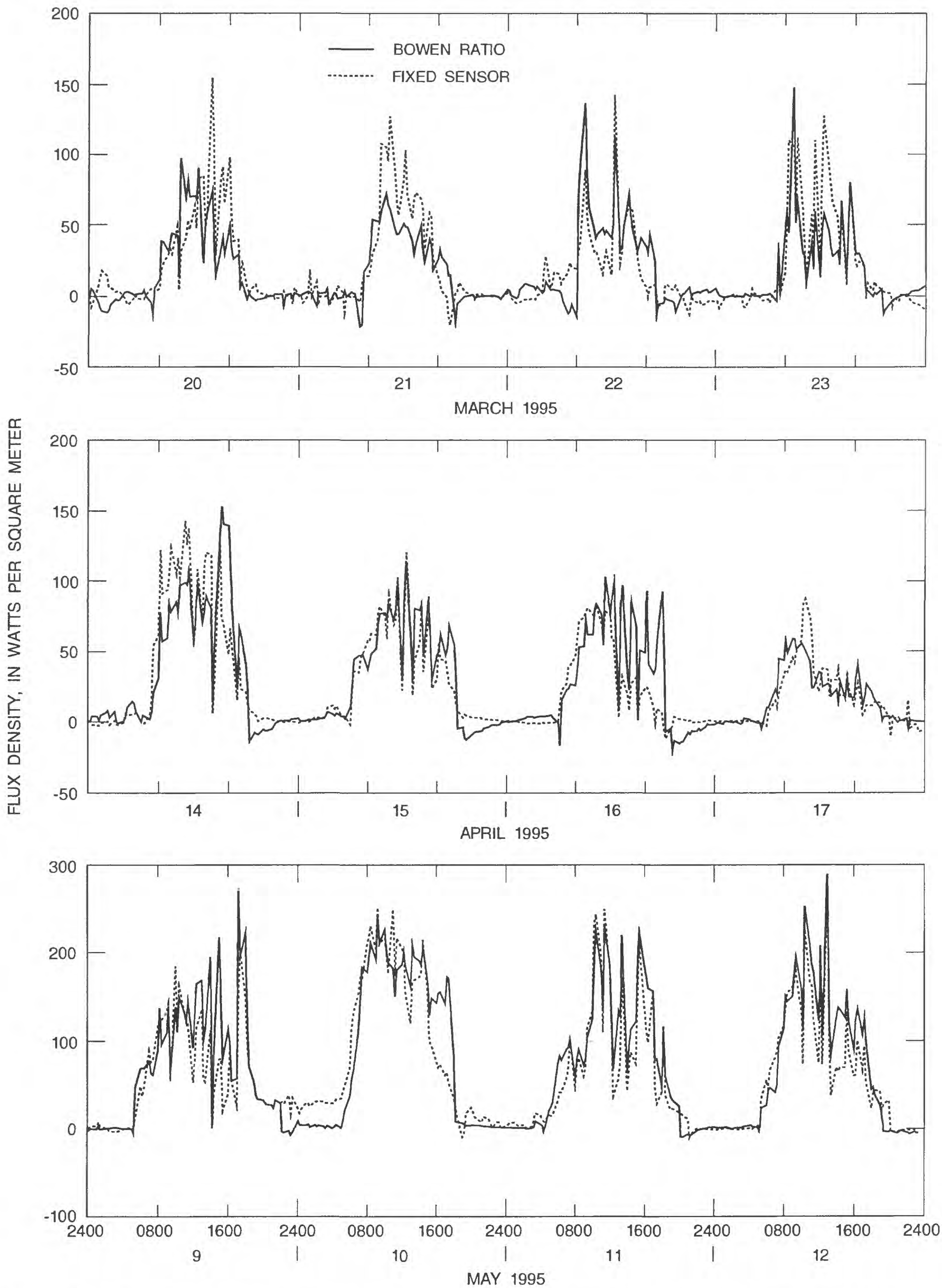


Figure 30.--Bowen-ratio and fixed-sensor latent-heat flux at Firewater Canyon site, March 20-23, April 14-17, and May 9-12, 1995.

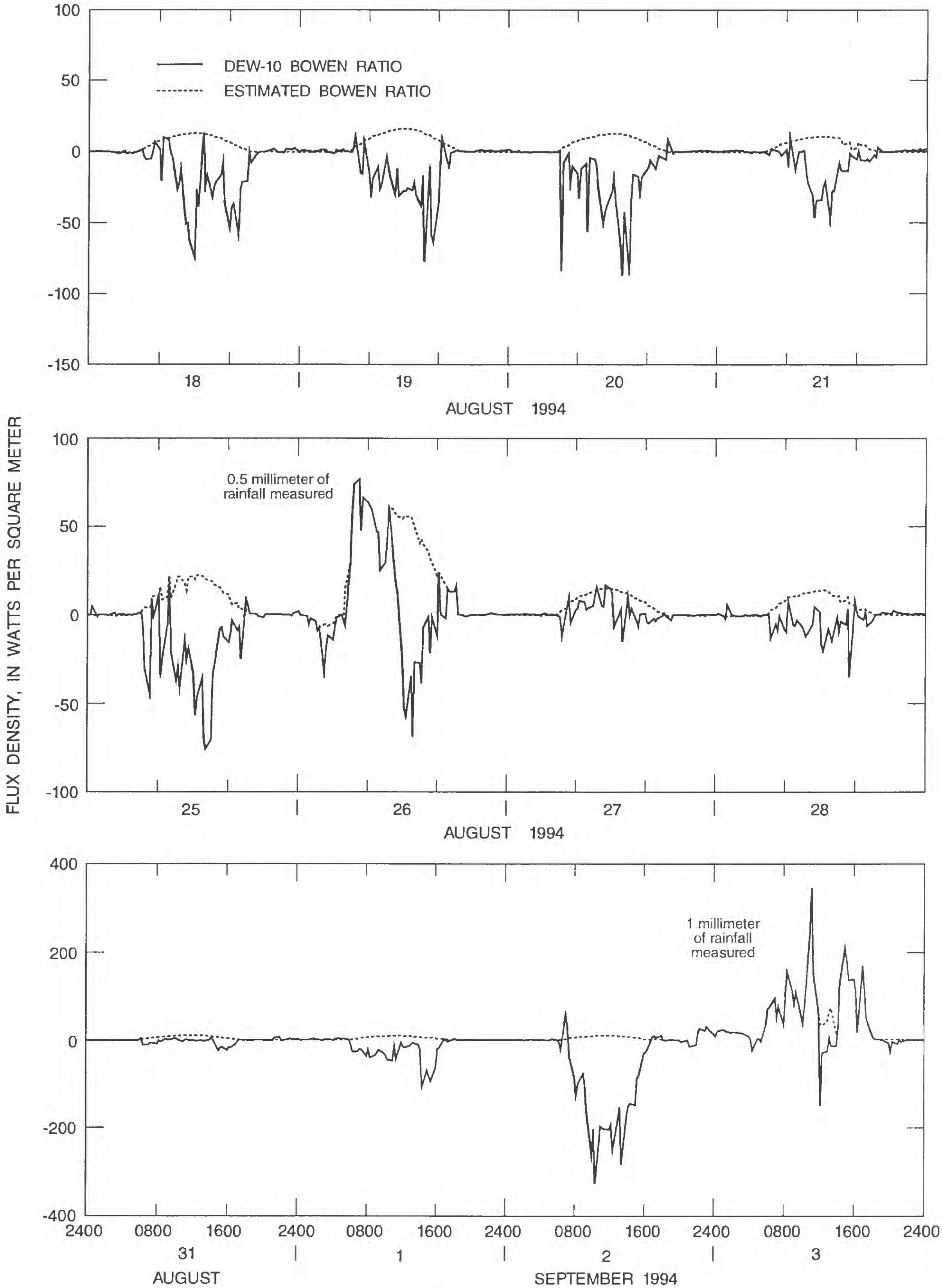


Figure 31.--DEW-10 and estimated Bowen-ratio latent-heat flux at Black Rock Valley site, August 18-21, August 25-28, and August 31 to September 3, 1994.

Comparison of Cumulative Evapotranspiration and Precipitation

Comparisons of cumulative ET and precipitation at the Black Rock Valley site from 1992 to 1995 showed that precipitation is probably not the sole source of water to the water budget at the Black Rock Valley site—ET exceeded precipitation every year. October 1 was used as the starting date for accumulating annual ET and precipitation. During late summer or early fall, soil-moisture storage, ET, and precipitation are usually all very low, making this period a good starting and stopping point when comparing cumulative precipitation and ET—these are periods when ET and soil-moisture storage change relatively little. Because of this, the water year (October to September) is more meaningful than the calendar year for determining annual cumulative precipitation and ET. Thus, for instance, in this report 1993 means the period October 1992 to September 1993 and 1994 means the period October 1993 to September 1994.

Annual cumulative ET and cumulative precipitation estimates were based on data collected at the Black Rock Valley site for each year except for part of 1992. For 1992, ET and precipitation data were not collected until March 1992, so estimates of precipitation from Moxee City (National Oceanic and Atmospheric Administration, 1991, 1992) were used for October 1991 to March 1992. Cumulative monthly ET for October 1991 to March 1992 was estimated from cumulative ET at the ALE Reserve for this period (Tomlinson, 1996a; Tomlinson, 1996b). ET during the October to March period is very low and only a small part of the cumulative ET for the year at the Black Rock Valley site. The estimates were made and included with the actual 1992 precipitation and ET estimates so 1992 would be comparable to 1993, 1994, and 1995. Cumulative precipitation, cumulative ET, and the ratio of ET-to-precipitation for the years were as follows:

Year	ET (mm)	Precipitation (mm)	Ratio (percent)
1992	352	214	164
1993	372	212	175
1994	199	122	163
1995	469	353	133
Average	348	225	155

The table shows that, based on the average annual precipitation of 225 mm at the Black Rock Valley site for 1992-95 (Moxee City long-term precipitation average is 198 mm (National Oceanic and Atmospheric Administration, 1994)), 1992 and 1993 were average years precipitation-wise, 1994 was a very dry year with about half the average precipitation, and 1995 was a wet year with over 50 percent more precipitation than average. The table above shows that there was a relation between ET and precipitation—the average precipitation years of 1992 and 1993 showed an average of 362 mm of ET, while the dry year of 1994 showed about half of the 362-mm average ET, and the wet year of 1995 showed about 30 percent more ET than the average. The ratios of ET-to-precipitation for each year appear to be unrelated to the amount of precipitation, varying by a maximum of about 14 percent from the average ratio.

The ratio of ET-to-precipitation for each year shows that annual ET exceeded annual precipitation from about 30 to 75 percent. This indicates either that precipitation received at the Black Rock Valley site is not the sole source of water in the water budget at the site, or that consistent instrument bias affected the precipitation and ET measurements. If precipitation is not the sole source of water at the Black Rock Valley site, additional water must come from other areas, possibly surface runoff or ground water from upland areas of the Yakima Ridge. Instrument bias in ET or precipitation measurements or advection influences at the Black Rock Valley site could cause ET to be overestimated or precipitation to be underestimated; these explanations were ruled out, however, after studies done at nearby sites from October 1994 to October 1995.

Precipitation and Evapotranspiration at the Bird Canyon, Black Rock Valley, and Firewater Canyon Sites

Two additional sites were set up from October 1994 to October 1995 to test for possible instrument error and to compare precipitation and ET. The two additional sites were the Bird Canyon site, located 0.8 km west of the Black Rock Valley site, and the Firewater Canyon site, located 2.5 km east of the Black Rock Valley site. Bowen-ratio and fixed-sensor instruments measured parameters to estimate ET with the Bowen-ratio method at all three sites. Two storage gages and two tipping-bucket gages were set up at each site, except at the Black Rock Valley site, where two storage gages and only one tipping-bucket gage were installed. Seasonal trends of ET were the same at the three sites—highest ET occurred in late spring, coinciding with plant growth, and lowest in fall or winter, coinciding with very dry or very cold conditions (table 3; fig. 32). Comparisons of tipping-bucket and storage-gage precipitation showed little difference. Comparisons of cumulative annual precipitation and ET showed some similarities, but also some significant differences. Analysis of daily energy-budgets and ET showed considerable differences in ET during different periods of the year at the three sites.

Tipping-Bucket and Storage-Gage Precipitation

From October 1994 to October 1995, precipitation measured by tipping-bucket gages was nearly the same as that measured by storage gages. Both types of gages had standard opening widths of 203 mm (8 inches). Two storage gages were installed about 8 m apart at ground level at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites. Two tipping-bucket gages were installed side- by-side at the Bird Canyon and Firewater Canyon sites, while one tipping-bucket gage was installed at the Black Rock Valley site. To reduce wind-induced losses in the precipitation catch, the tipping-bucket gages were set about 0.5 m above the ground surface, with the tops of the gages just below the top of the vegetative canopy at each site. Data from the two tipping-bucket gages at the Bird Canyon and Firewater Canyon sites were averaged to provide one value for each site (table 3). Precipitation in the storage gages was measured, then discarded during each site visit. About 2.5 mm of oil was added to the storage gages to reduce evaporation losses. The amounts of precipitation from the two storage gages at each site were averaged to provide one value for each site. The precipitation recorded by each of the tipping-bucket gages was also averaged for each site for the period between site visits and compared with the storage-gage precipitation. Results for gages at the Bird Canyon site (BIRD), Black Rock Valley site (BLACK), and Firewater Canyon site (FIRE) were as follows:

Date	Precipitation (mm)									
	Tipping bucket			Storage gage				Percent tipping/storage		
	Bird Canyon site	Black Rock Valley site	Fire Canyon site	Bird Canyon site	Black Rock Valley site	Fire Canyon site		Bird Canyon site	Black Rock Valley site	Fire Canyon site
11-01-94	42.4	44.2	45.0	46.2	46.0	46.0		96	96	98
03-15-95	149	144	148	133	132	138		112	109	107
03-29-95	2.7	2.3	2.8	3.3	3.6	3.6		81	64	78
04-19-95	17.0	18.3	17.0	17.5	17.5	17.8		97	104	96
05-09-95	45.5	48.8	50.7	39.6	42.7	47.0		115	114	108
07-06-95	26.8	30.0	31.0	27.4	29.2	33.5		98	103	92
08-02-95	15.8	16.3	15.8	7.9	7.9	8.9		200	207	177
09-08-95	31.2	33.5	36.3	29.2	31.2	34.0		107	107	107
10-04-95	14.2	14.7	15.2	15.5	16.5	16.3		92	89	94
10-24-95	14.5	14.5	15.5	15.2	15.2	16.3		95	95	95
Total	359	367	377	335	342	361	Average	107	107	104

Table 3.--*Daily and monthly precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995*

[All values are in millimeters; BRD, Bird Canyon site; BLK, Black Rock Valley site; FRW, Firewater Canyon site; --, insufficient data to calculate daily or monthly values; *, estimated or partly estimated; TR, data indicates trace of precipitation]

	1994																	
	October						November						December					
	Precipitation			Evapotranspiration			Precipitation			Evapotranspiration			Precipitation			Evapotranspiration		
Day	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW
1	--	--	--	--	--	--	0.25	0.25	0.00	1.03	1.43	1.16	0.00	0.00	0.00	0.33	0.20	0.18
2	--	--	--	--	--	--	0.00	0.00	0.00	0.63	0.69	0.65	0.25	0.25	0.13	0.56	0.51*	0.36
3	--	--	--	--	--	--	0.00	0.00	0.00	0.49	0.31	0.42	0.00	0.00	0.00	0.28	0.19	0.23
4	--	--	--	--	--	--	0.76	1.27	1.02	0.42	0.53	0.31	0.00	0.00	0.00	0.22	0.27	0.22
5	--	--	--	--	--	--	0.00	0.00	0.13	0.49	0.55	0.46	0.00	0.00	0.00	0.20	0.01	0.07
6	--	--	--	--	--	--	0.25	0.25	0.25	0.45	0.75*	0.41	0.13	0.00	0.25	0.22	0.17	0.09
7	--	--	--	--	--	--	0.13	0.00	0.00	0.51	0.16	0.36	0.00	0.00	0.00	0.35	0.15	0.18
8	--	--	--	--	--	--	0.89	0.76	1.27	0.51	0.05	0.32	0.51	0.76	0.38	0.40	0.28	0.24
9	--	--	--	--	--	--	3.18	3.30	2.79	0.38	0.26	0.36	0.00	0.00	0.25	0.18	0.02	0.05
10	--	--	--	--	--	--	0.38	0.51	0.64	0.69	0.43	0.65	0.00	0.00	0.00	0.26	0.51	0.06
11	--	--	--	--	--	--	0.76	0.51	0.64	0.38	0.72	0.32	0.00	0.00	0.00	0.06	0.32*	0.07
12	--	--	--	--	--	--	0.00	0.25	0.00	0.58	0.44	0.47	0.64	0.00	0.00	0.02	0.21*	0.23
13	--	--	--	--	--	--	0.00	0.00	0.00	0.51	0.34	0.48	0.25	0.00	0.13	0.09	0.17	0.08
14	--	--	--	--	--	--	0.00	0.00	0.00	0.35	0.38*	0.22	0.00	0.00	0.13	0.21	0.38	0.04
15	--	--	--	--	--	--	6.98	5.59	6.86	0.54	0.42	0.41	4.70	5.84	5.46	0.46	0.65	0.25
16	--	--	--	--	--	--	0.00	0.25	0.25	0.58	0.15	0.29	7.49	6.60	6.73	0.43	0.55	0.38
17	--	--	--	--	--	--	0.13	0.00	0.00	0.67	0.85	0.32	1.40	1.27	1.52	0.55	0.28	0.53
18	--	--	--	--	--	--	0.00	0.00	0.13	0.53	0.23	0.23	4.32	4.57	3.68	0.65	0.83	0.19
19	--	--	--	--	--	--	0.13	0.25	0.00	0.44	0.14*	0.34	0.00	0.00	0.00	0.27	0.08	0.06
20	--	--	--	--	--	--	0.00	0.00	0.13	0.26	0.03	0.10	0.00	0.00	0.00	0.25	0.23	0.09
21	--	--	--	--	--	--	0.00	0.00	0.00	0.33	0.20	0.23	0.00	0.00	0.00	0.19	0.23	0.11
22	0.00	0.00	0.00	0.24	0.07	0.04	0.00	0.00	0.00	0.39	0.27	0.22	0.00	0.00	0.00	0.57	0.11	0.40
23	0.00	0.00	0.00	0.00	0.08	0.04	0.00	0.00	0.00	0.40	0.12*	0.27	0.25	0.00	0.13	0.57	0.97*	0.63
24	0.00	0.00	0.00	0.00	0.09	0.01	0.00	0.00	0.51	0.38	0.57	0.20	0.00	0.00	0.13	0.44	0.68	0.32
25	0.00	0.00	0.00	0.06	0.20	0.06	1.27	1.52	0.64	0.56	0.74*	0.44	0.00	0.00	0.00	0.30	0.85	0.35
26	9.40	9.40	10.16	0.41	0.40	0.58*	1.02	1.02	1.02	0.91	0.83	0.42	8.64	7.62	8.38	0.19	0.54	0.21
27	22.10	23.37	23.11	0.32	0.64	0.43*	2.29	2.79	2.54	0.88	0.69*	0.70	0.25	0.25	0.25	0.31	0.09	0.20
28	0.00	0.00	0.00	1.00	1.23	1.12*	0.00	0.00	0.00	0.44	0.74*	0.08	0.00	0.00	0.00	0.41	0.42	0.27
29	0.00	0.00	0.00	0.59*	0.62	0.54	2.54	3.30	2.79	0.52	0.31*	0.22	0.00	0.00	0.00	0.28	0.16	0.23
30	0.00	0.00	0.00	0.59*	0.50	0.44	0.13	0.00	0.00	0.31	0.15	0.07	0.00	0.00	0.00	0.33	0.22	0.34
31	10.92	11.43	11.68	0.92	1.18	0.86*							0.00	0.00	0.00	0.06	0.14	0.23
TOT	--	--	--	--	--	--	21.09	21.82	21.61	15.56	13.48	11.13	28.83	27.16	27.55	9.64	10.42	6.89

Table 3.--*Daily and monthly precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995--Continued*

	1995																	
	January						February						March					
	Precipitation			Evapotranspiration			Precipitation			Evapotranspiration			Precipitation			Evapotranspiration		
Day	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW
1	0.00	0.00	0.00	0.15	0.00	0.00	3.56	3.81	3.05	0.24	0.00	0.00*	0.00	0.00	0.00	0.67	1.38	0.37
2	0.00	0.00	0.00	0.08	0.00	0.00	0.13	0.00	0.00	0.84	0.89	0.68	0.00	0.00	0.00	0.32	0.84	0.23
3	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.46	0.52	0.27	0.00	0.00	0.00	0.35	0.75	0.28
4	0.00	0.00	0.00	0.10	0.00	0.05	0.00	0.00	0.00	0.66	0.87*	0.43	0.00	0.00	0.00	0.79	0.55*	0.52
5	0.00	0.00	0.00	0.11	0.00	0.02	0.00	0.00	0.00	0.66	0.66*	0.56	0.00	0.00	0.00	0.64	0.50	0.37
6	0.00	0.00	0.00	0.19	0.00	0.07	0.00	0.00	0.00	0.83	0.67*	0.53*	0.00	0.00	0.00	0.71	0.58	0.46
7	0.00	0.00	0.00	0.35	0.09	0.05*	7.87	7.37	7.11	1.06	0.22	0.57*	0.00	0.00	0.00	0.82	0.62	0.38
8	6.10	5.59	3.43	0.13	0.00	0.00*	0.00	0.00	0.13	0.50	0.75*	0.34	1.65	1.27	1.65	0.44	0.26	0.23
9	9.91	8.89	14.22	0.46	0.40	0.23*	0.00	0.00	0.00	0.60	0.52*	0.61	10.80	10.16	11.05	1.00	0.62	0.45*
10	5.59	5.84	5.33	0.67	0.80*	0.62*	0.00	0.00	0.00	0.45	0.66	0.51	6.86	7.11	6.10	0.73	0.49	0.42*
11	4.70	4.57	4.46	0.79	0.72*	0.25*	0.76	0.51	1.14	0.94	1.15	0.64*	0.25	0.00	0.13	1.31	0.95	1.14
12	1.52	1.52	1.27	0.45	0.25	0.31*	0.13	0.00	0.00	0.49	0.51	0.55	0.25	0.25	0.00	1.14	1.17	1.12
13	4.57	3.56	4.06	0.25	0.22	0.13*	0.00	0.00	0.00	0.23	0.33	0.37	1.02	1.02	1.27	1.28	1.06	0.90
14	3.56	3.56	3.18	0.79	0.50	0.40*	1.02	1.78	2.79	0.39	0.32	0.27	4.32	4.32	5.08	1.10	0.97	0.79
15	0.00	0.00	0.13	0.79	0.78	0.46*	0.25	0.25	0.38	1.16	0.70*	0.38	0.00	0.00	0.00	1.39	1.31	1.90
16	0.25	0.25	0.13	1.06	1.38	0.53	0.13	0.25	0.13	1.00	1.36	0.10	0.00	0.00	0.00	0.84	1.01	0.93
17	0.00	0.00	0.00	0.59	0.77	0.20*	0.00	0.00	0.00	1.11	1.19	0.41	0.00	0.00	0.00	0.87	0.77	0.70
18	0.25	0.25	0.38	0.50	0.15	0.14*	0.00	0.00	0.25	0.93	0.60	0.12	0.25	0.25	0.38	0.93	0.84	0.86
19	0.00	0.00	0.00	0.81	0.35*	0.48	0.00	0.00	0.00	1.02	0.41	0.30	0.00	0.00	0.00	1.29	1.04	0.84
20	0.00	0.00	0.00	1.02	1.08*	0.41	0.00	0.00	0.00	0.55	1.07	0.32	2.41	2.03	2.16	1.01	1.50	0.78
21	0.00	0.00	0.00	0.48	0.00	0.33	0.00	0.00	0.00	0.60	0.99	0.84	0.00	0.00	0.00	0.90	0.98	0.79
22	0.00	0.00	0.00	0.32	0.00	0.66	0.00	0.00	0.00	0.59	0.95	0.76	0.00	0.00	0.00	0.61	0.98	0.56
23	0.00	0.00	0.00	0.31	0.15	0.16	0.00	0.00	0.00	0.74	1.22	0.48	0.00	0.00	0.25	0.93	0.67	0.76
24	0.00	0.00	0.00	0.22	0.13	0.27	0.00	0.00	0.00	0.72	1.32	0.69	0.00	0.00	0.00	0.99	0.93	0.65
25	0.38	0.25	0.51	0.21	0.55	0.01*	0.00	0.00	0.00	0.58	0.83	0.64	0.00	0.00	0.00	0.81	0.85	0.40
26	2.54	2.79	2.29	0.25	0.55	0.06*	0.00	0.00	0.00	0.82	1.03	0.48	0.00	0.00	0.00	0.86*	0.69	0.46
27	0.25	0.25	0.25	0.30	0.61	0.11*	0.00	0.00	0.00	0.37	1.17	0.40	0.00	0.00	0.00	0.94*	1.02	0.43
28	7.11	6.60	5.72	0.03	0.12	0.00*	0.00	0.00	0.00	0.35	1.22	0.60	0.00	0.00	0.00	0.69*	0.89	0.14
29	3.81	4.32	4.46	0.74	0.86	0.58*							0.00	0.00	0.00	1.18	0.91	0.37
30	5.84	5.59	5.33	0.81	0.78	0.20*							0.00	0.00	0.00	0.91	1.13	0.98*
31	3.56	3.05	3.30	1.05	0.00	0.34*							0.00	0.00	0.00	1.06	1.37	0.50
TOT	59.94	56.88	58.45	14.04	11.24	7.08	13.85	13.97	14.98	18.89	22.13	12.85	27.81	26.41	28.07	27.51	27.63	19.71

Table 3.--*Daily and monthly precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995--Continued*

	1995																	
	April						May						June					
	Precipitation			Evapotranspiration			Precipitation			Evapotranspiration			Precipitation			Evapotranspiration		
Day	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW
1	0.00	0.00	0.00	1.89	0.94	0.86*	2.67	2.79	2.79	1.51	1.78	1.84	0.00	0.00	0.00	5.12	3.35*	2.26
2	0.00	0.00	0.00	1.40	0.69	0.46	0.13	0.25	0.00	3.11	4.26	2.51	0.00	0.00	0.00	3.33	1.98	1.08
3	0.00	0.00	0.00	2.07	0.87	0.71	TR	TR	0.00	2.87	3.41	2.01	0.00	0.00	0.00	4.17	3.78*	1.06
4	0.00	0.00	0.00	1.98	0.63	0.44*	1.27	1.78	1.52	2.26	2.29	1.92	1.78	2.03	2.03	2.77	3.00*	1.21*
5	0.38	0.51	0.38	1.03	0.38*	0.37*	0.25	0.00	0.25	1.92	2.06	1.54	0.51	0.51	0.38	3.26	4.65	1.73*
6	0.00	0.00	0.00	2.18	0.96*	0.98*	0.00	0.00	0.00	3.90*	4.51	2.01	10.54	12.70	13.34	1.43	2.62	1.83
7	0.89	0.76	1.02	2.44	0.84	1.56*	0.00	0.00	0.13	2.89	2.94	1.96	0.51	0.25	0.00	2.49	2.08	2.54*
8	0.00	0.00	0.00	1.70	0.55*	0.73*	0.51	0.76	0.64	2.52	2.12	1.47	0.00	0.00	0.00	2.85	1.82	2.15
9	0.00	0.00	0.00	2.12	0.94	0.48*	8.38	9.65	9.52	3.03	2.92	2.40	0.00	0.00	0.00	2.67	1.72	2.68
10	0.76	0.76	0.76	0.77*	0.65	0.49	0.13	0.00	0.25	3.61	4.59	3.06	1.52	1.78	1.52	2.48	1.87	3.10
11	0.00	0.00	0.00	2.20*	1.36	1.13	0.89	1.02	1.14	2.68	2.63	2.42	0.13	0.25	0.13	3.14	2.10	3.23
12	13.97	13.97	13.34	1.33	1.88	0.97	0.00	0.00	0.00	4.10	4.37	2.39	0.00	0.00	0.00	2.31	1.80	2.79
13	0.89	1.02	0.76	3.04	2.40	2.29	2.03	2.03	2.41	5.30	5.05	3.06	0.00	0.00	0.00	1.29	1.60	1.70
14	0.00	0.00	0.00	1.37	2.74	1.25	0.00	0.00	0.00	5.45	4.03	3.32	2.03	1.78	1.52	1.44	2.58	1.70
15	0.00	0.00	0.00	1.52*	2.38	1.06	0.00	0.00	0.00	4.28	3.05	3.05	0.13	TR	0.13	1.65	1.14	1.64
16	0.00	0.00	0.00	2.03	3.01	0.93	0.00	0.00	0.00	4.91	3.11	2.85	0.51	0.76	1.27	1.90	1.65	2.67
17	0.00	0.00	0.00	1.39	1.49	0.57	0.00	0.00	0.00	5.35	4.88	2.65	0.00	0.00	0.00	1.50	1.86	2.05
18	0.00	0.00	0.00	2.27	3.17	0.86	0.00	0.00	0.00	4.63	3.65	2.34	0.00	0.00	0.00	1.75	2.57	1.77
19	1.02	1.27	0.76	2.02	2.37	0.95*	0.00	0.00	0.00	5.19	4.20	2.63	0.00	0.00	0.00	0.98	1.15	1.66
20	8.76	9.14	8.51	1.49	2.22	1.74	0.00	0.00	0.00	5.67	4.30	2.94	0.00	0.00	0.00	1.00	1.25	1.67
21	0.00	0.00	0.00	2.73	3.38	2.37	0.00	0.00	0.00	5.12	3.68	2.80	0.00	0.00	0.00	1.45	1.63	2.20
22	0.00	0.00	0.00	3.11	3.46	2.05	0.00	0.00	0.00	5.45	4.06	2.93	0.00	0.00	0.00	1.68	2.14	2.40
23	0.00	0.00	0.00	3.31	2.95	1.84	0.00	0.00	0.00	5.71	4.32	3.09	0.00	0.00	0.00	2.02	2.70	2.93
24	0.00	0.00	0.00	4.02	3.57	2.03	0.00	0.00	0.00	5.69	4.36	2.93	0.00	0.00	0.00	1.97	2.78	2.81
25	0.00	0.00	0.00	2.93	2.48	1.60	1.52	2.03	2.29	4.52	2.91	2.60	0.00	0.00	0.00	1.85	2.26	2.83
26	0.00	0.00	0.00	3.10	2.82	1.77	0.00	0.00	0.00	5.14	4.46	3.10	0.00	0.00	0.00	1.52	3.06	2.61
27	3.81	3.81	4.83	1.62	2.59	1.27	0.00	0.00	0.00	5.35	4.28	3.15	0.00	0.00	0.00	1.65	1.91	2.35
28	14.99	15.49	16.76	1.57	1.58	1.50	0.00	0.00	0.00	5.69	4.33*	3.52	0.00	0.00	0.00	1.48	1.43	2.18
29	4.70	5.08	5.72	1.97	2.87	1.68	0.00	0.00	0.00	6.02	4.57*	3.83	0.00	0.00	0.00	1.47	1.60	2.16
30	0.00	0.00	0.00	2.85	3.34	2.78	0.00	0.00	0.00	5.38	4.15*	3.47	0.00	0.00	0.00	1.54	1.92	2.43
31							0.00	0.00	0.00	5.36	4.58*	3.30						
TOT	50.17	51.81	52.84	63.45	59.51	37.72	17.78	20.31	20.94	134.61	115.85	83.09	17.66	20.06	20.32	64.16	66.00	65.42

Table 3.--*Daily and monthly precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995--Continued*

	1995																	
	July						August						September					
	Precipitation			Evapotranspiration			Precipitation			Evapotranspiration			Precipitation			Evapotranspiration		
Day	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW	BRD	BLK	FRW
1	0.00	0.00	0.00	1.61	2.58	2.57	0.00	0.00	0.00	0.57	1.41	0.72	0.00	0.00	0.00	0.53	1.34	0.20
2	TR	TR	TR	1.34	1.20	1.78	0.00	0.00	0.00	0.63	1.25	0.60	0.00	0.00	0.00	0.48	0.99	0.31
3	0.00	0.00	0.00	1.00	1.53	1.43	0.00	0.00	0.00	0.44	0.98	0.73	0.00	0.00	0.00	0.21	0.97*	0.21
4	0.00	0.00	0.00	0.91	1.85	1.54	0.00	0.00	0.00	0.62	1.51	0.68	0.00	0.00	0.00	0.54	1.04	0.44
5	0.00	0.00	0.00	0.98	1.91	1.64	0.00	0.00	0.00	0.53	0.74	0.81	0.00	0.00	0.00	0.32	1.14	0.07
6	4.57	4.83	4.57	2.03	2.98	2.77	0.00	0.00	0.00	0.15	0.39	0.48	14.48	14.73	14.22	0.29	1.01	0.50
7	0.00	0.00	0.25	2.01	2.27	2.25	TR	TR	0.00	0.63	1.29	0.17	10.67	11.94	14.22	0.86	1.43	1.37
8	6.86	8.13	8.13	2.49	2.33	2.44	0.00	0.00	0.00	0.51	1.54	0.07	0.00	0.00	0.00	0.73	1.90	1.45
9	7.37	6.35	5.59	3.05	4.35	2.68	0.00	0.00	0.00	0.64	1.40	0.38	0.00	0.00	0.00	1.27	2.18	1.20
10	0.00	0.00	0.00	2.52	2.38	2.43	6.10	6.86	7.87	1.30	1.38	1.54	0.00	0.00	0.00	1.63	2.48	1.09
11	0.00	0.00	0.00	1.97	1.56	1.78	0.00	0.00	0.00	2.40	1.96	1.92	0.00	0.00	0.00	1.27	1.36	1.00
12	0.00	0.00	0.00	1.73	1.23	1.53	0.00	0.00	0.00	0.81	0.66	0.75	0.00	0.00	0.00	1.56*	1.41	0.87
13	0.00	0.00	0.00	1.36	1.25	1.52	0.00	0.00	0.00	0.96	2.08	0.56	0.00	0.00	0.00	1.64*	1.27*	0.69
14	0.00	0.00	0.00	1.36	1.79	1.50	0.00	0.00	0.00	0.88	1.48	0.62	0.00	0.00	0.00	1.95	1.71	0.73
15	0.00	0.00	0.00	1.31	1.46	1.24	0.00	0.00	0.00	0.77	1.27	0.29	0.00	0.00	0.00	2.08	1.44*	0.73
16	0.00	0.00	0.00	1.62	1.61*	1.31	0.00	0.00	0.00	0.68	1.51	0.24	0.00	0.00	0.00	1.87	1.10*	0.66
17	0.00	0.00	0.00	1.41	1.32*	1.32	0.00	0.00	0.00	0.62	1.01	0.18	0.00	0.00	0.00	1.67	1.19	0.63
18	0.00	0.00	0.00	1.28	1.51	1.62	0.00	0.00	0.00	0.63	1.76	0.18	0.00	0.00	0.00	1.39	0.88	0.63*
19	0.00	0.00	0.00	1.16	1.30	1.48	0.00	0.00	0.00	0.65	1.99	0.26	0.00	0.00	0.00	1.35	1.25*	0.63*
20	TR	TR	TR	0.89	1.01*	1.41	0.00	0.00	0.00	0.79	2.09	0.48	0.00	0.00	0.00	1.15	0.99*	0.61*
21	0.00	0.00	0.00	1.12	1.51	1.25	0.00	0.00	0.00	0.72	1.29	0.48	0.00	0.00	0.00	1.00	1.09*	0.58*
22	0.00	0.00	TR	0.69	1.12	0.84	0.00	0.00	0.00	0.64	1.80	0.43	0.00	0.00	0.00	0.95*	1.16	0.40*
23	0.00	0.00	0.00	0.69	0.85	0.83	0.00	0.00	0.00	0.39	0.54	0.59	0.00	0.00	0.00	1.05*	1.00*	0.47*
24	0.00	0.00	0.00	0.70	1.32	0.60	0.00	0.00	0.00	0.41	1.16	0.20	0.00	0.00	0.00	0.94*	0.91*	0.45*
25	0.00	0.00	0.00	0.71	1.81	0.91	0.00	0.00	0.00	0.52	1.24	0.24	0.00	0.00	0.00	0.80*	0.73*	0.37*
26	1.52	1.78	1.78	2.43	1.98	1.86	0.00	0.00	0.00	0.47	1.33	0.16	0.00	0.00	0.00	0.89*	1.18	0.39*
27	0.00	0.00	0.00	0.87	1.81	0.56	0.00	0.00	0.00	0.47	1.63	0.19	3.30	3.56	3.30	1.45	1.61*	1.17
28	0.00	0.00	0.00	1.01	1.71	1.04	TR	TR	TR	0.42	1.24	0.13	0.76	1.27	1.27	1.28	1.35	0.87*
29	0.00	0.00	0.00	0.50	0.65	0.28	TR	TR	TR	0.79	1.40	0.37	0.00	0.00	0.00	1.15	1.10	1.20*
30	0.00	0.00	0.00	0.59	1.66	0.51	0.00	0.00	0.00	0.51	1.70	0.12	1.02	0.76	1.02	1.46	1.72	1.32*
31	0.00	0.00	0.00	0.60	1.55	0.63	0.00	0.00	0.00	0.46	0.34	0.04						
TOT	20.32	21.09	20.32	41.94	53.39	45.55	6.10	6.86	7.87	21.01	41.37	14.59	30.23	32.26	34.03	33.76	38.20	21.24

Table 3.--*Daily and monthly precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995--Continued*

	1995					
	October					
	Precipitation			Evapotranspiration		
Day	BRD	BLK	FRW	BRD	BLK	FRW
1	0.00	0.00	0.00	0.95	1.21	0.88*
2	3.56	3.56	3.81	1.26	1.20	0.76*
3	5.59	5.59	5.84	1.60	2.93	1.75*
4	0.00	0.00	0.00	1.03	1.94	0.47*
5	0.00	0.00	0.00	1.14	1.46	0.67
6	0.00	0.00	0.00	1.21	1.35	0.51
7	0.00	0.00	0.00	1.20	1.66	0.38
8	0.00	0.00	0.00	0.83	0.77	0.32
9	0.00	0.00	0.00	0.99	1.12	0.36
10	2.03	2.03	2.54	0.67	0.67	0.52
11	5.08	5.08	5.33	0.84	1.43	1.73
12	0.25	0.25	0.00	1.27	2.18	1.05
13	0.00	0.00	0.00	1.08	1.89	0.49
14	0.00	0.00	0.00	1.02	1.59	0.47
15	0.00	0.00	0.00	1.01	1.45	0.55
16	0.00	0.00	0.00	1.12	1.84	0.67
17	7.11	7.11	7.62	0.55	0.76	0.72
18	0.00	0.00	0.00	1.61	2.50	0.77
19	0.00	0.00	0.00	1.15	1.87	0.92
20	0.00	0.00	0.00	1.00	0.89	0.55
21	0.00	0.00	0.00	1.02	1.02	0.39
22	0.00	0.00	0.00	0.90	1.51	0.33
23	0.00	0.00	0.00	0.77	0.88	0.36
24	0.00	0.00	0.00	0.94*	1.24*	0.25
25	--	--	--	--	--	--
26	--	--	--	--	--	--
27	--	--	--	--	--	--
28	--	--	--	--	--	--
29	--	--	--	--	--	--
30	--	--	--	--	--	--
31	--	--	--	--	--	--
TOT	--	--	--	--	--	--

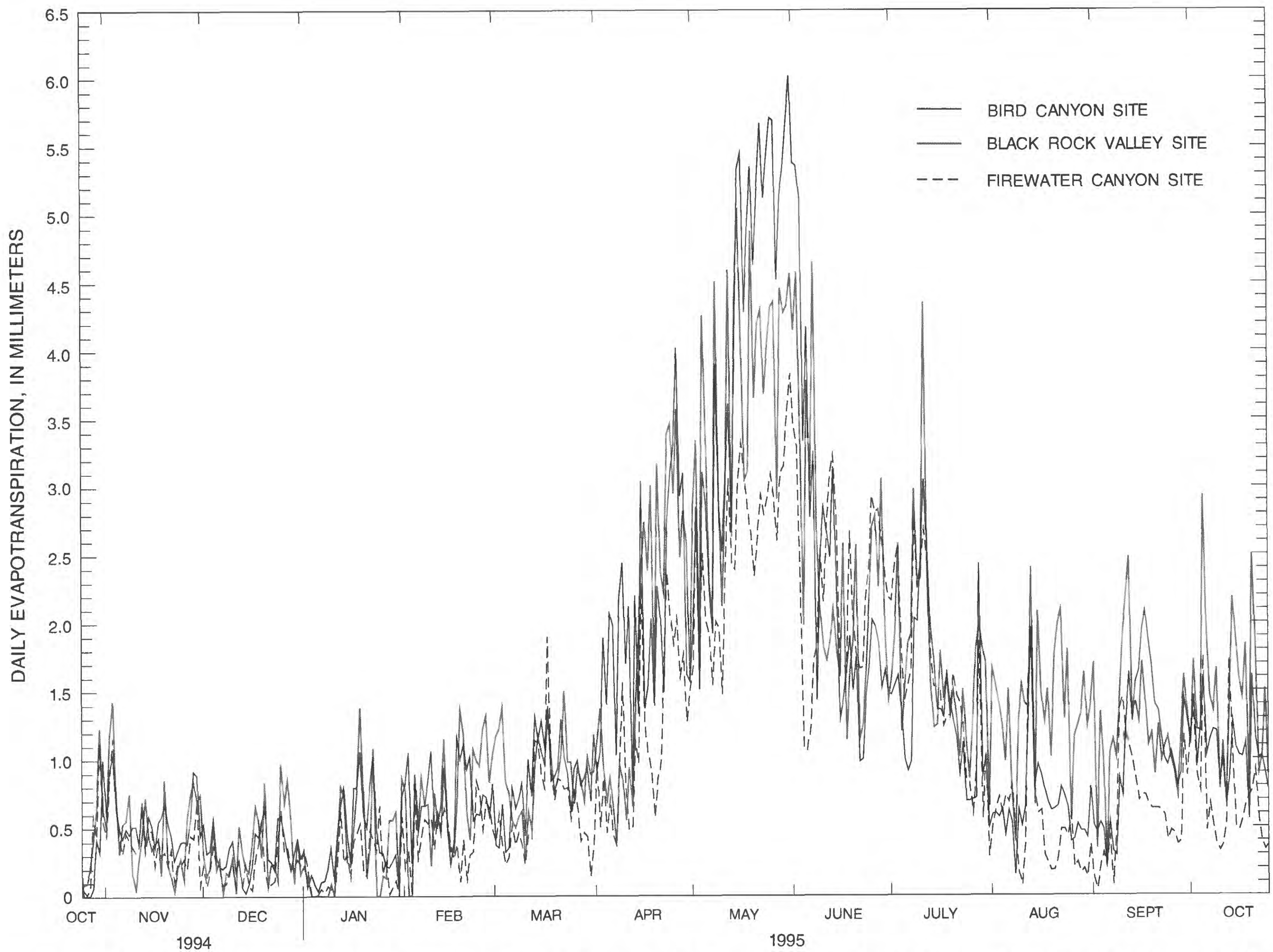


Figure 32.--Evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995.

The table shows that tipping-bucket precipitation was usually within about 10 percent of storage-gage precipitation. Two exceptions occurred: one in the March 29 measurements, and one in the August 2 measurements. In the first exception, the March 29 measurements for the tipping-bucket gages are about 20-35 percent less than those measured by the storage gages. Only two rainfalls occurred between March 15 and 29, one on March 18, and one on March 20. On both days, rainfall was accompanied by very high winds—up to 11 m/s on March 20. Therefore, it is possible that very high winds still cause some reduction in tipping-bucket precipitation catch, even when the gages are placed just below the top of the canopy. Also, the percentage differences calculated for the March 29 measurements may be somewhat misleading due to the small quantity of precipitation in the gages—less than 4 mm. The other exception was in the August 2 readings, when tipping-bucket precipitation was about 200 percent of storage-gage precipitation. The big difference is most likely caused by evaporation from the storage gages. The most significant rainfall for the period July 6 to August 2 was on July 7-8. Nearly a month of sunny skies and warm weather followed July 6 until the next site visit on August 2, and the small amount of oil used in the storage gages may not have been adequate to prevent evaporation during this period.

In summary, however, precipitation measured by the tipping-bucket and storage gages was very close. The tipping-bucket gages averaged only 6 percent more precipitation than the storage gages for the period October 22, 1994, to October 24, 1995. If the August 2 readings are eliminated from the analysis as outliers, the average difference is reduced to only 4 percent. Because of the close results obtained between the two precipitation measurement methods, no adjustments were made in estimating cumulative precipitation, when comparing it to cumulative ET. In another study in similar terrain and vegetation, a 10-percent underestimate by the tipping-bucket gage was found, compared with data from weighing lysimeters (Tomlinson, 1995, p. 50). However, the tipping-bucket gage in this other study was set higher than the top of the canopy, so wind may have had a significant effect in reducing the precipitation catch.

Daily and Cumulative Annual Precipitation and Evapotranspiration

Comparisons of precipitation at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites were nearly the same, but ET comparisons differed considerably between the sites (table 3; fig. 33). On an annual basis, cumulative precipitation differed by less than 4 percent at the three sites. Daily precipitation at the Black Rock Valley site agreed well with that at the Bird Canyon site (r^2=0.99) and the Firewater Canyon site (r^2=0.98). However, these high r^2 values are due primarily to many days of zero precipitation at the three sites. Though daily values of ET at the Black Rock Valley and Bird Canyon sites differed considerably (r^2=0.77), cumulative ET matched within about 4 percent for October 1994 to September 1995. However, Firewater Canyon site ET did not match well with ET at the Black Rock Valley site on a daily (r^2=0.69) or cumulative basis. Cumulative ET at the Firewater Canyon site was only about 70 percent of that at the Black Rock Valley and Bird Canyon sites.

For the period October 22, 1994, to September 5, 1995, cumulative ET, cumulative precipitation, and the ratio of ET-to-precipitation were as follows:

Site	ET (mm)	Precipitation (mm)	Ratio (percent)
Black Rock Valley	432	311	139
Bird Canyon	417	306	136
Firewater Canyon	309	318	97.2

Rainfall totalling over 25 mm on September 6-7, 1995 increased the surface (top 0.10 m soil layer) soil moisture from 4 percent to about 16 percent at each of the sites. This rainfall, in effect, ended the dry late summer and fall season, when ET and soil moisture are generally at their lowest level for the year. Because of the rainfall on September 6-7, 1995, and on many days after that, the remainder of the data-collection period to October 24 was not considered in the tabled cumulative ET and precipitation, although the ET-to-precipitation ratios for the Black Rock Valley and Bird Canyon sites would change only 1 and 3 percent, respectively, if those data were included.

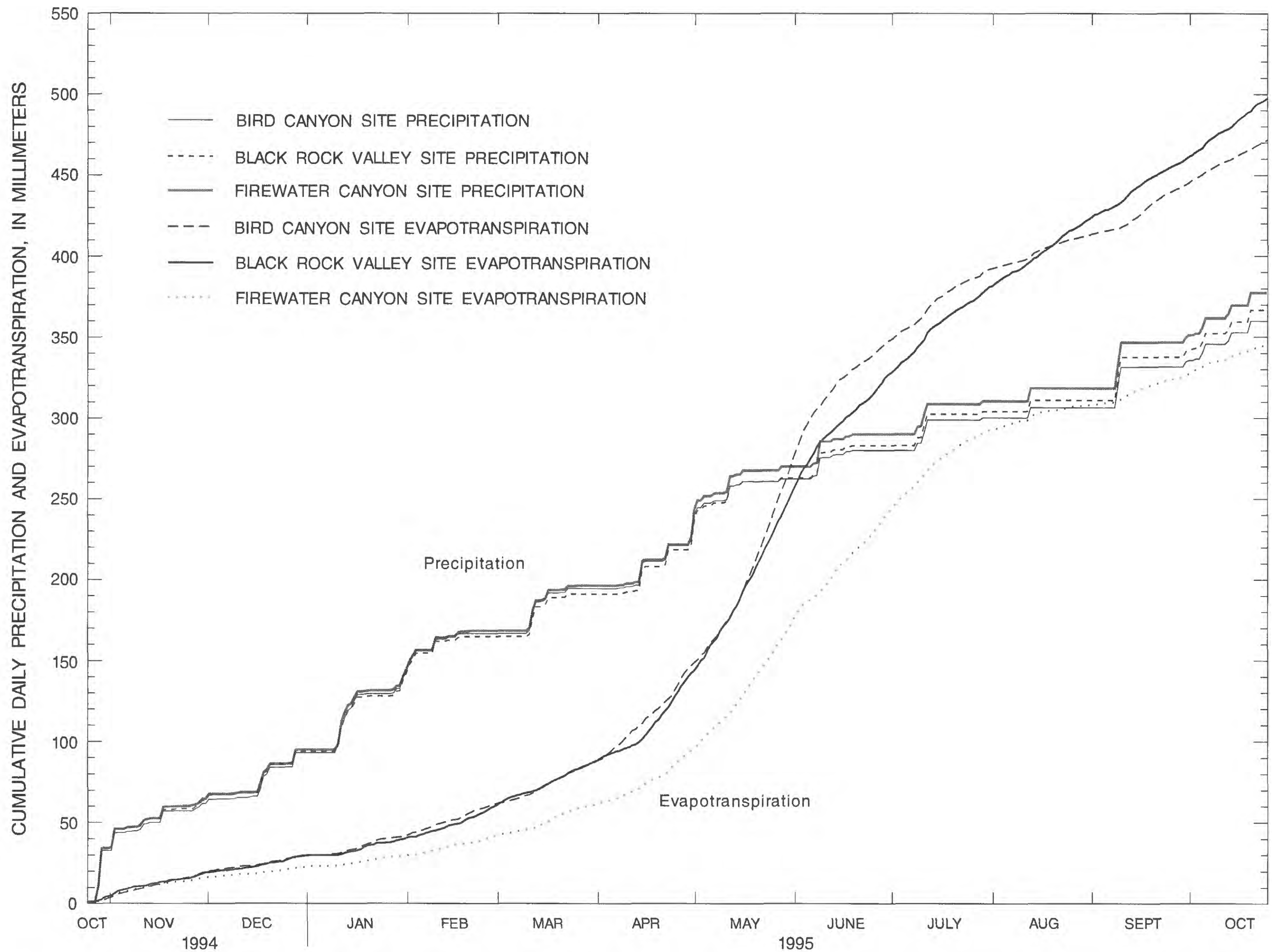


Figure 33.--Cumulative daily precipitation and evapotranspiration at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, October 22, 1994, to October 24, 1995.

For October 22, 1994, to September 5, 1995, cumulative precipitation did not differ much between the three sites, but cumulative ET did. Cumulative precipitation differed by an average of less than 4 percent at all three sites. However, cumulative ET at the Firewater Canyon site was 25 and 28 percent less than ET at the Bird Canyon and Black Rock Valley sites, respectively. Cumulative ET at the Black Rock Valley and Bird Canyon sites varied by less than 4 percent. As at the Black Rock Valley site, ET-to-precipitation ratios at the Bird Canyon site showed that more ET than precipitation occurred annually. However, the ET-to-precipitation ratio at the Firewater Canyon site was very similar to those observed at sites on the ALE Reserve (Tomlinson, 1995, p. 65-68; Tomlinson, 1996a; Tomlinson, 1996b), where nearly 100 percent of the annual precipitation becomes ET. Apparently, the area surrounding the Bird Canyon and Black Rock Valley sites receives additional water for ET, perhaps from surface runoff or ground water from upland areas of the Yakima Ridge, whereas the Firewater Canyon site does not receive additional water. This result is significant in that it shows that even areas with similar vegetation, terrain, and precipitation in close proximity do not necessarily have the same ET regimes.

Even more differences result when 20-minute and daily energy-budget fluxes and ET estimates at the three sites are compared. Four periods, one each in March, May, June, and August 1995 illustrate the similarities and differences in site variables, on a 20-minute and daily basis at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites. Even though net radiation and soil-heat flux were often about the same at each site, latent-heat flux (and, therefore, sensible-heat flux) were often very different. Thus, daily ET estimates were also different. The exception was on rainy or cloudy days, on many of which latent-heat flux and ET were about the same at all the sites.

Comparisons of Energy-Budget Fluxes and Evapotranspiration

Energy-budget flux comparisons showed that latent-heat flux and ET varied between the Black Rock Valley, Bird Canyon, and Firewater Canyon sites despite very similar net radiation and soil-heat flux. Comparison of daily ET totals for March 16-24, May 13-30 (this period is broken into two 9-day periods, May 13-21 and May 22-30, in the table so the results are comparable to the other 9-day periods), June 15-23, and August 8-16, 1995 show that sometimes latent-heat flux and ET were nearly the same for all sites, and sometimes they were very different, as shown in the following table.

	Total ET for the period, in millimeters		
Period	Black Rock Valley site	Bird Canyon site	Firewater Canyon site
March 16-24	8.72	8.37	6.87
May 13-21	35.95	45.90	28.57
May 22-30	37.44	48.95	28.65
June 15-23	17.10	13.93	18.99
August 8-16	13.28	8.95	6.37

March 16-24, 1995

The period March 16-24, 1995, is representative of late winter and early spring energy budgets and ET at the study sites. Daily ET is low (generally less than 1 mm/day) because of low net radiation and other fluxes caused by many cloudy days and cold nights (table 3; fig. 34). Maximum daytime air temperatures averaged 9-12 °C, and nighttime low temperatures ranged from -1 to 5°C. During the period, only light rain fell, the maximum being 3 mm on March 20. Net radiation and soil-heat flux were nearly the same at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites (fig. 35), as was latent- heat flux (fig. 36). Total daily ET for the period March 16-24 was similar at the three sites—Firewater Canyon site ET was about 80 percent of the ET at the Black Rock Valley and Bird Canyon sites, which were within 5 percent of each other. At this time of year, most plants are probably still dormant and the similarity of latent-heat fluxes and ET at the three sites may simply reflect similar evaporation from the soil surface at the sites.

May 13-30, 1995

ET at the three sites was highest for the year during the period May 13-30. Peak daily ET was 5.05 mm at the Black Rock Valley site on May 13, 6.02 mm at the Bird Canyon site on May 29, and 3.83 mm at the Firewater Canyon site on May 29 (table 3). These high values of ET are due to high transpiration from the growing vegetation, along with high evaporation from the soil surface. Although no measurements of plant transpiration alone were made at the sites, transpiration was concluded to be high because surface soils were generally dry while plants were in full growth. Since plant roots effectively absorb water from subsurface soils, high transpiration would result as long as subsurface soil moisture is available.

From May 13-30, 1995, high net radiation allowed by many clear days (figs. 37-38), combined with daily maximum temperatures of 24-28°C, and moist subsurface soils, helped provide conditions for high ET. Comparing net radiation and soil-heat flux at the three sites (figs. 39-40) shows that net radiation was generally highest at the Bird Canyon site, while soil-heat flux was the lowest (during daytime) at that site. This was probably due to the green grass cover at the Bird Canyon site reflecting less solar radiation than areas with bare ground and sagebrush, and to the shading effect of the grasses on the soil surface, which lessened solar warming of the soil.

High transpiration from the grasses at the Bird Canyon site was reflected in the high latent-heat flux (figs. 41-42) and ET (table 3) for the period. As actively growing plant cover increases, so does the percent of ET due to transpiration, so it is reasonable that the Bird Canyon site, with 75 to 90 percent plant cover, should have the highest spring ET of the three sites. Bird Canyon site ET was about 30 percent more than ET at the Black Rock Valley site and over 60 percent more than ET at the Firewater Canyon site. The only exceptions to this were on cloudy days, such as May 15-16 (fig. 41) and rainy days, such as May 25 (fig. 42), when latent-heat flux and ET were reasonably close at all three sites. These exceptions are reasonable because with cloudy, wet weather, plant metabolic activity is reduced and the plants do not need to transpire as much to cool themselves; therefore, transpiration is probably much less of a factor in ET on cloudy days. Most of the ET in cloudy, wet weather is probably evaporation.

June 15-23, 1995

The period June 15-23 represents a time when the grasses are senescing while sagebrush plants begin to lose their spring leaves in response to drier, warmer conditions. This period in June shows the cloudy, cool conditions that can sometimes occur, such as June 19, within only a few days of very warm, dry, sunny conditions, such as June 22 (fig. 43). Air temperatures varied widely, with daily maximums ranging from 13-28°C and minimums from 4-13°C. Correspondingly, ET was variable, ranging from about 1-3 mm/day. The large burst of ET at the Bird Canyon site in late May, with values of 4-6 mm/day ended quickly in June as the grasses used up the available water and began to turn brown. From June 15-23, ET at the Bird Canyon site ranged from less than 1 to about 2 mm/day. The sagebrush, on the other hand, probably continued to transpire, resulting in ET of 2-3 mm/day. The different color of the grasses—golden brown instead of the deep green in May—also showed up in the net radiation comparisons. Net radiation was nearly the same at all three sites, as it had been in March (fig. 44). Bird Canyon site soil-heat flux was lower during the day and higher at night than at the other two sites because of the insulating effect of the grass canopy on the soil surface.

This is the only period besides March when ET at the two sagebrush sites was fairly close. ET at the Firewater Canyon site was only 11 percent more than ET at the Black Rock Valley site for the June 15-23 period and is shown in the close agreement of latent-heat flux at the two sites (fig. 45). The Bird Canyon site showed about 20 percent less ET than the Black Rock Valley site and nearly 30 percent less than the Firewater Canyon site for this period.

August 8-16, 1995

The energy budget for the Bird Canyon site for August 8-16, 1995 (fig. 46) shows clear, sunny days with very low latent-heat flux on August 8 and 9, followed by a very cloudy day on August 10, when about 7 mm of rain fell at the sites. On August 10, latent-heat flux closely approached, or slightly exceeded, net radiation. For the periods when latent-heat flux exceeded net radiation, additional energy may have been provided by soil-heat flux or advected sensible-heat flux. The days after this rainfall were mostly clear to partly cloudy, and latent-heat flux gradually decreased each succeeding day as soils dried. Maximum daily air temperatures ranged from about 20-27°C, and minimums ranged from 7-10°C. Net radiation was nearly identical at all three sites, while soil-heat flux continued to be somewhat less at the Bird Canyon site than at the Black Rock Valley and Firewater Canyon sites (fig. 47). (Text continued on p. 85.)

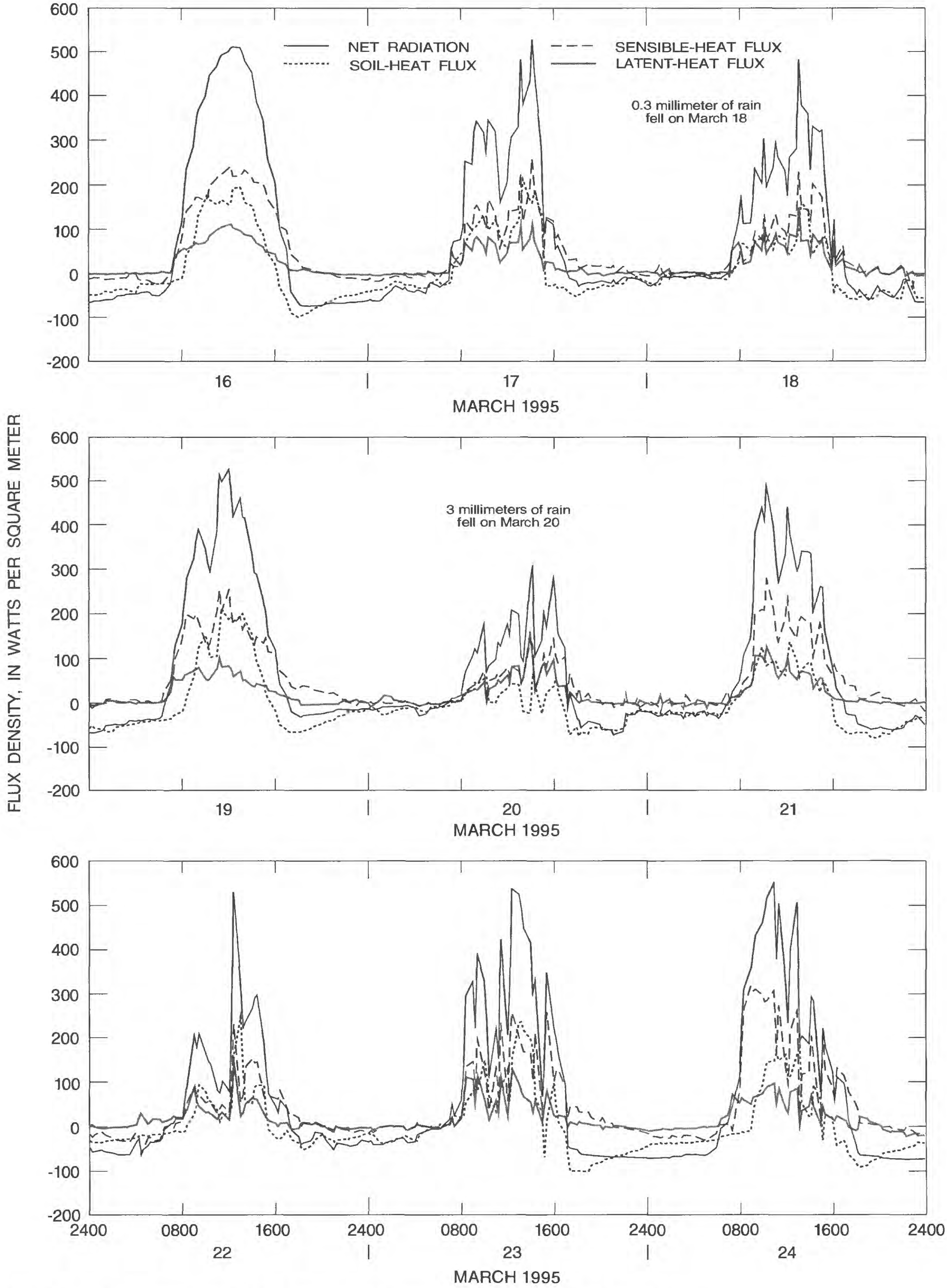


Figure 34.--Energy budget at Firewater Canyon site, March 16-24, 1995.

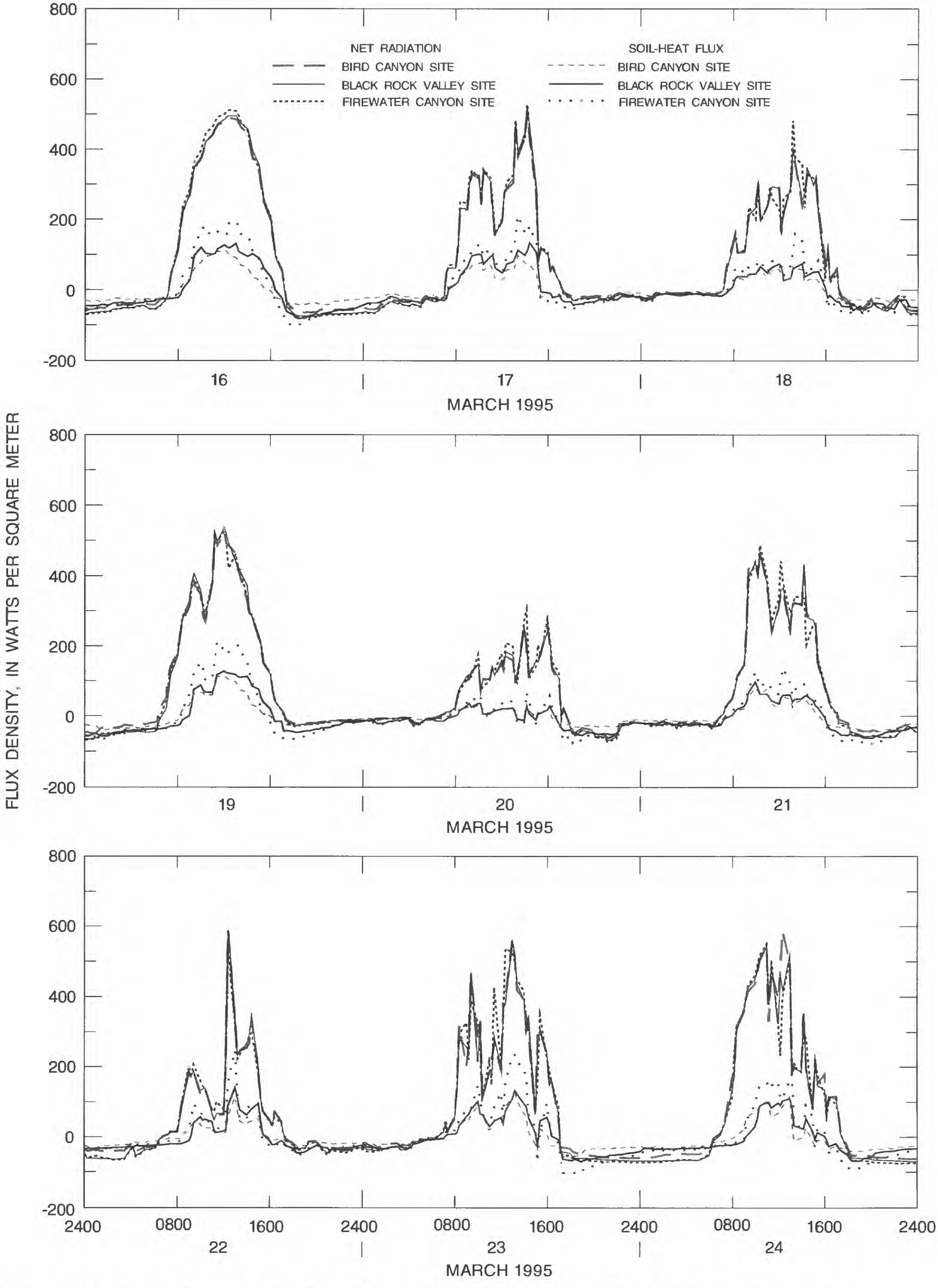


Figure 35.--Net radiation and soil-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, March 16-24, 1995.

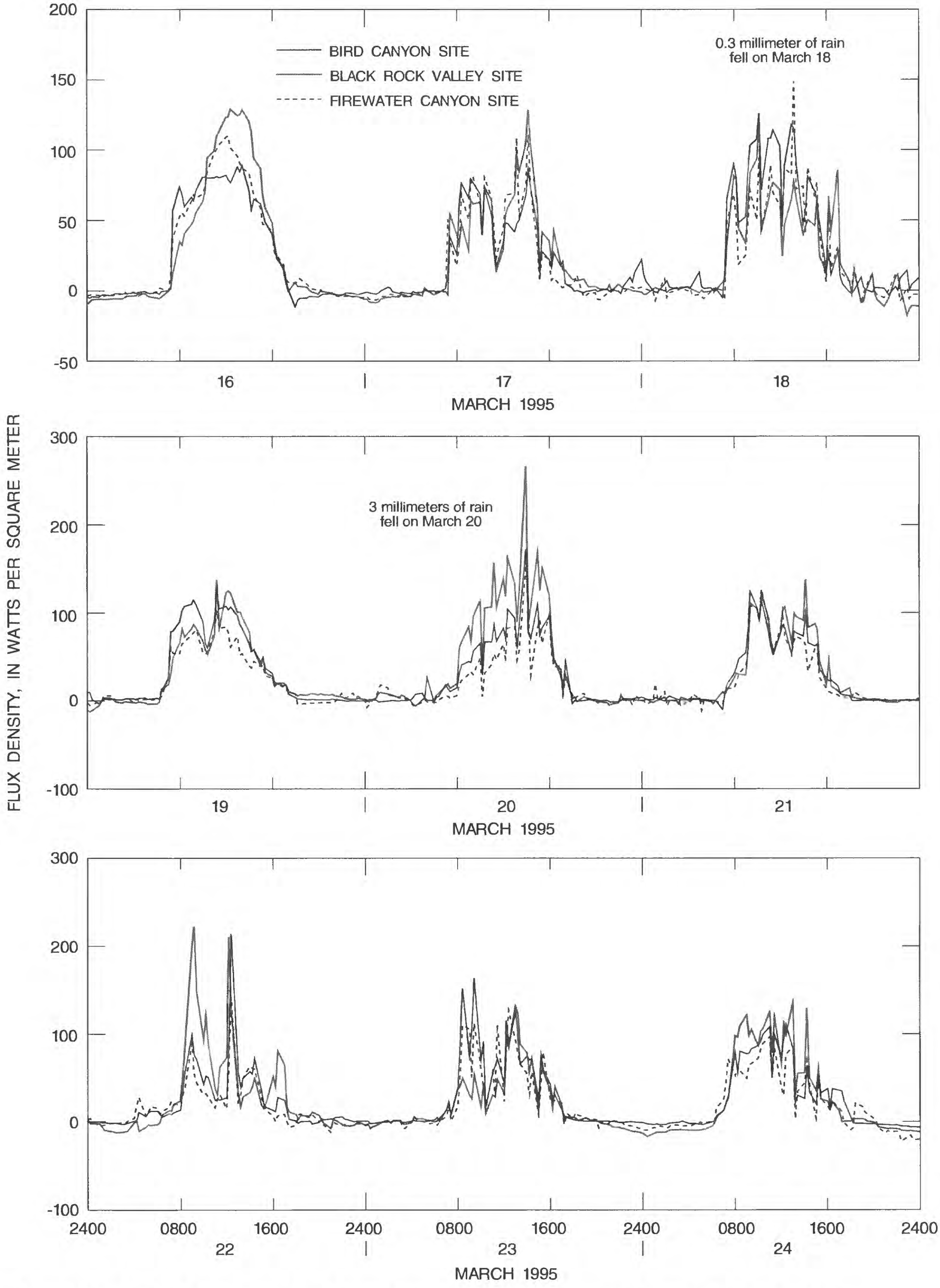


Figure 36.--Latent-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, March 16-24, 1995.

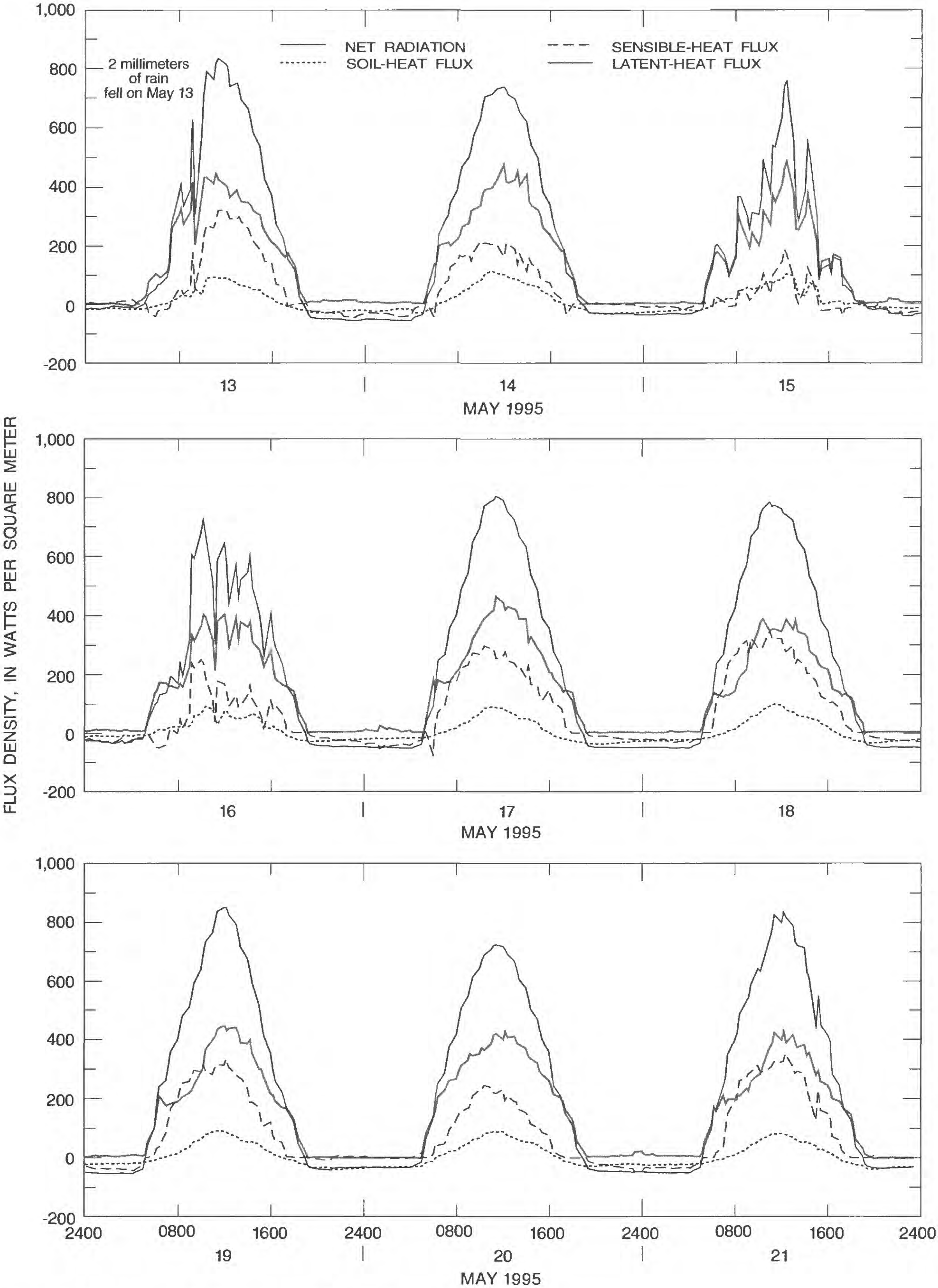


Figure 37.--Energy budget at Bird Canyon site, May 13-21, 1995.

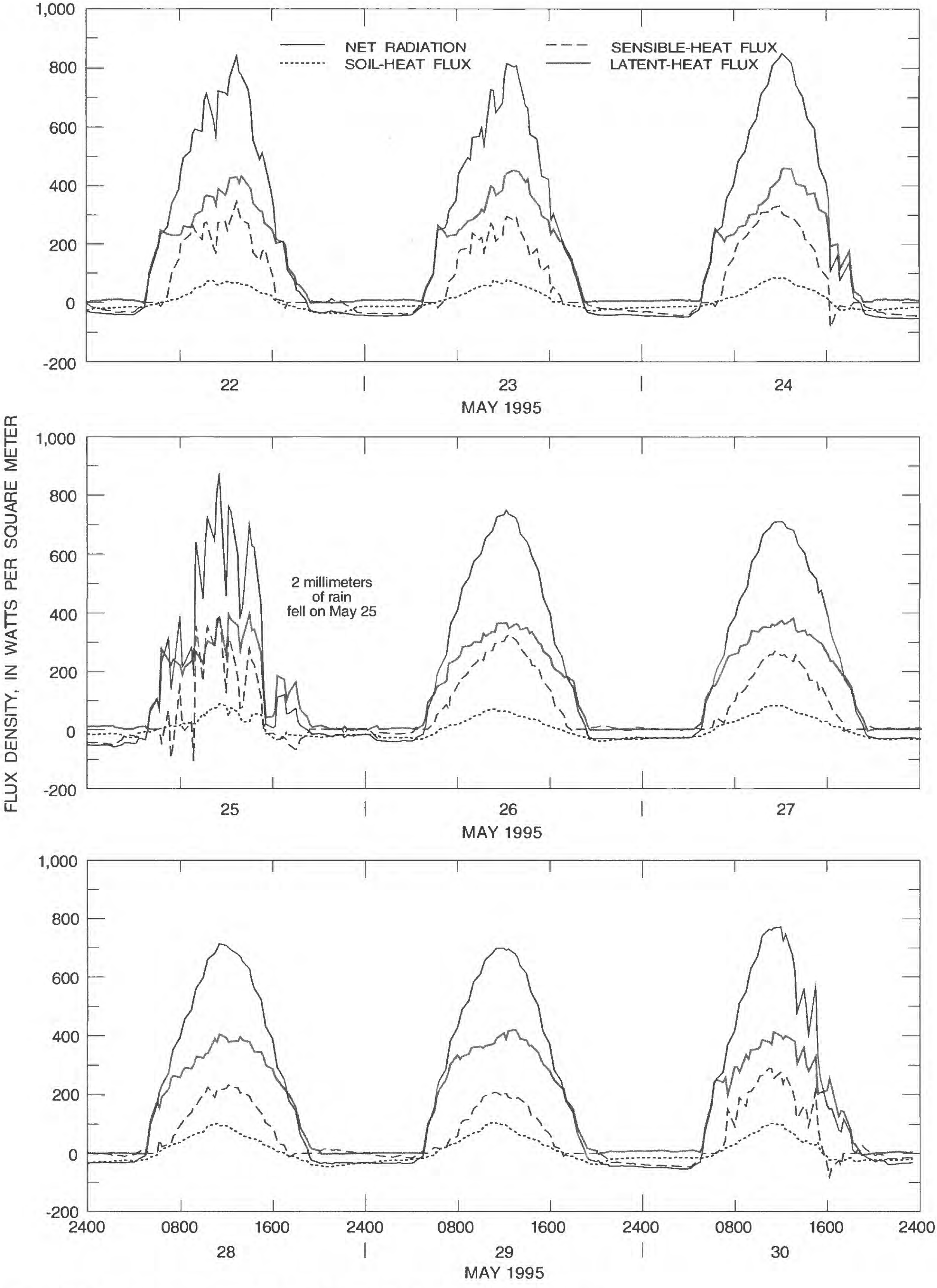


Figure 38.--Energy budget at Bird Canyon site, May 22-30, 1995.

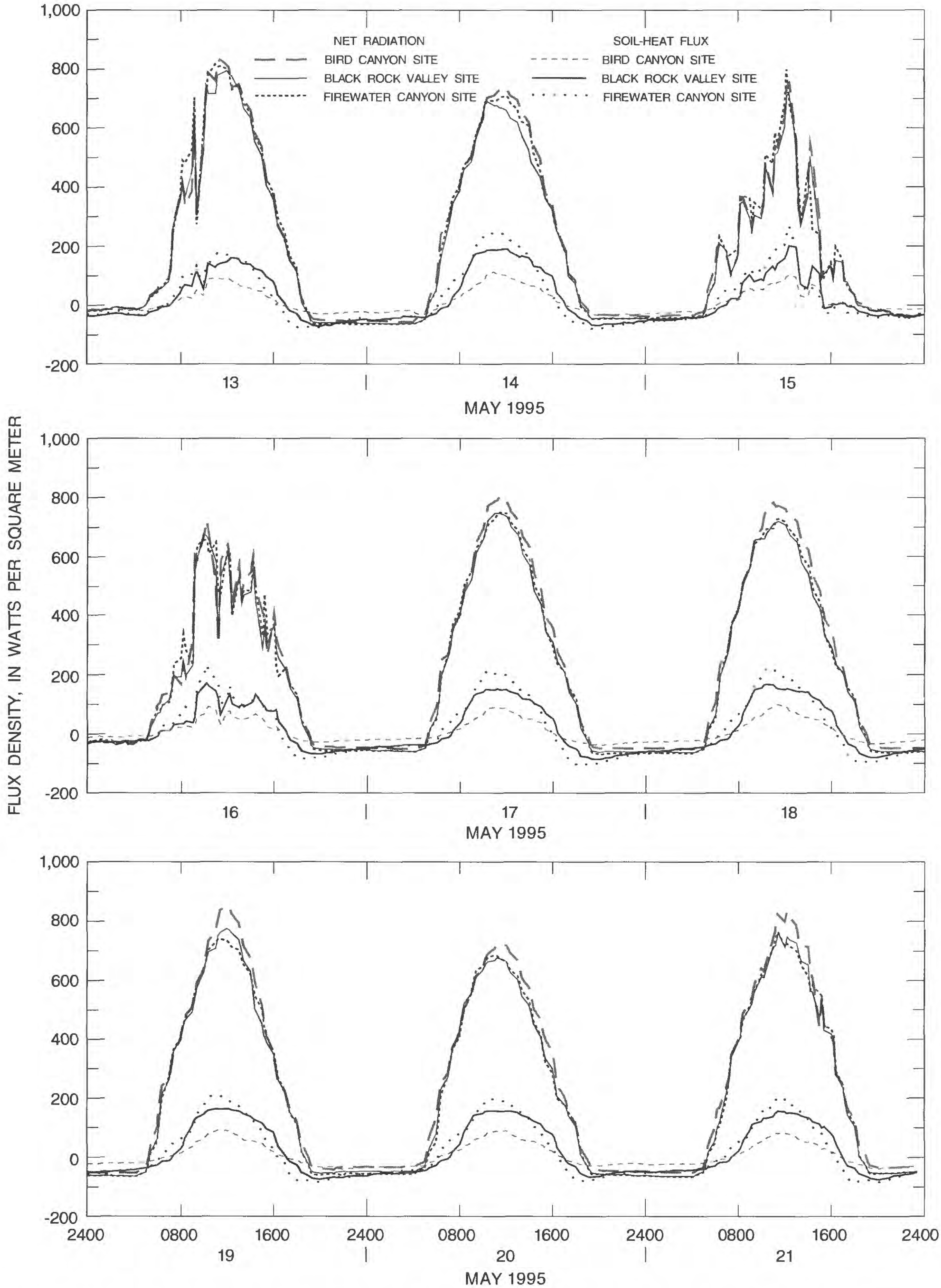


Figure 39.--Net radiation and soil-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, May 13-21, 1995.

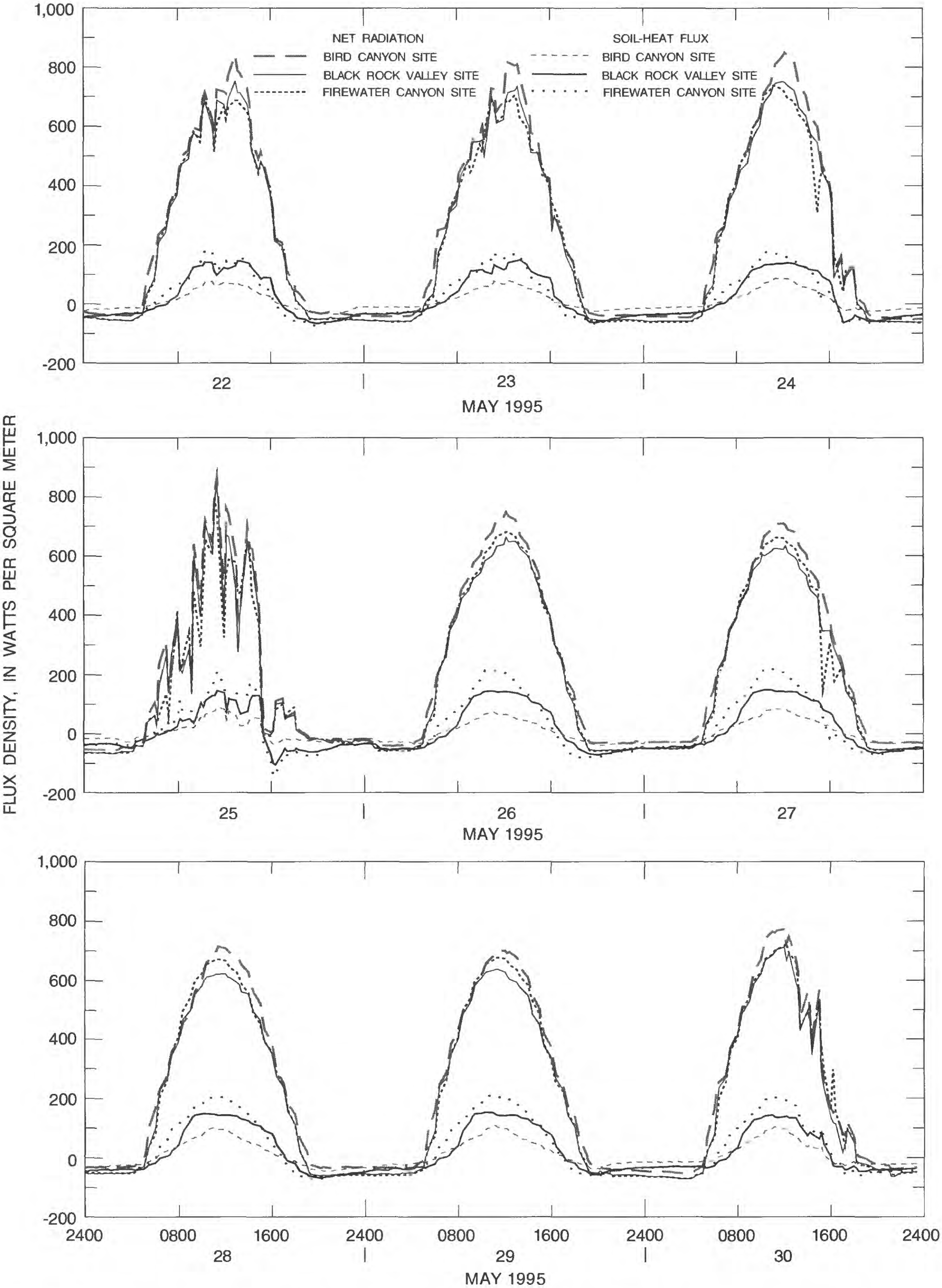


Figure 40.--Net radiation and soil-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, May 22-30, 1995.

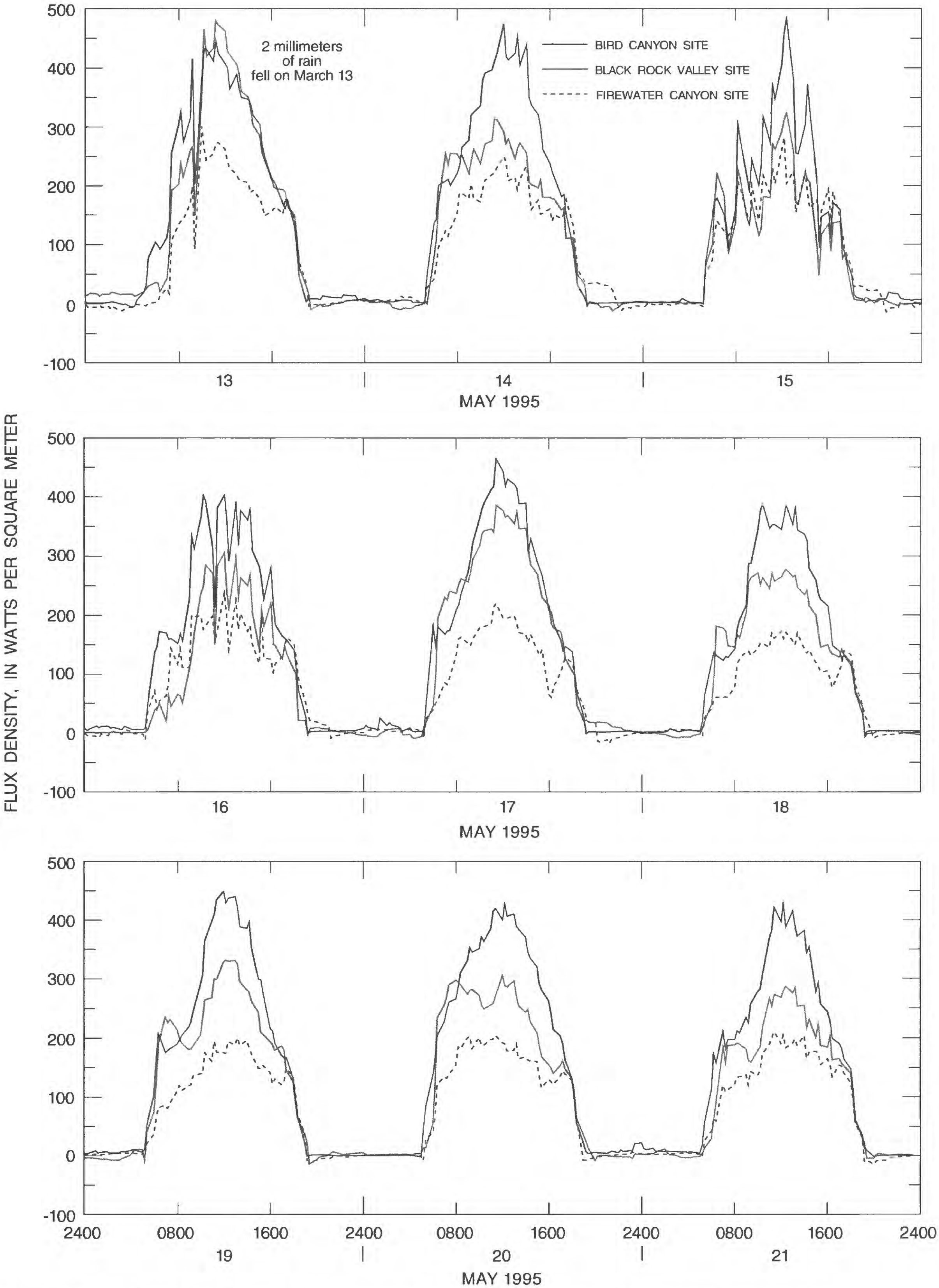


Figure 41.--Latent-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, May 13-21, 1995.

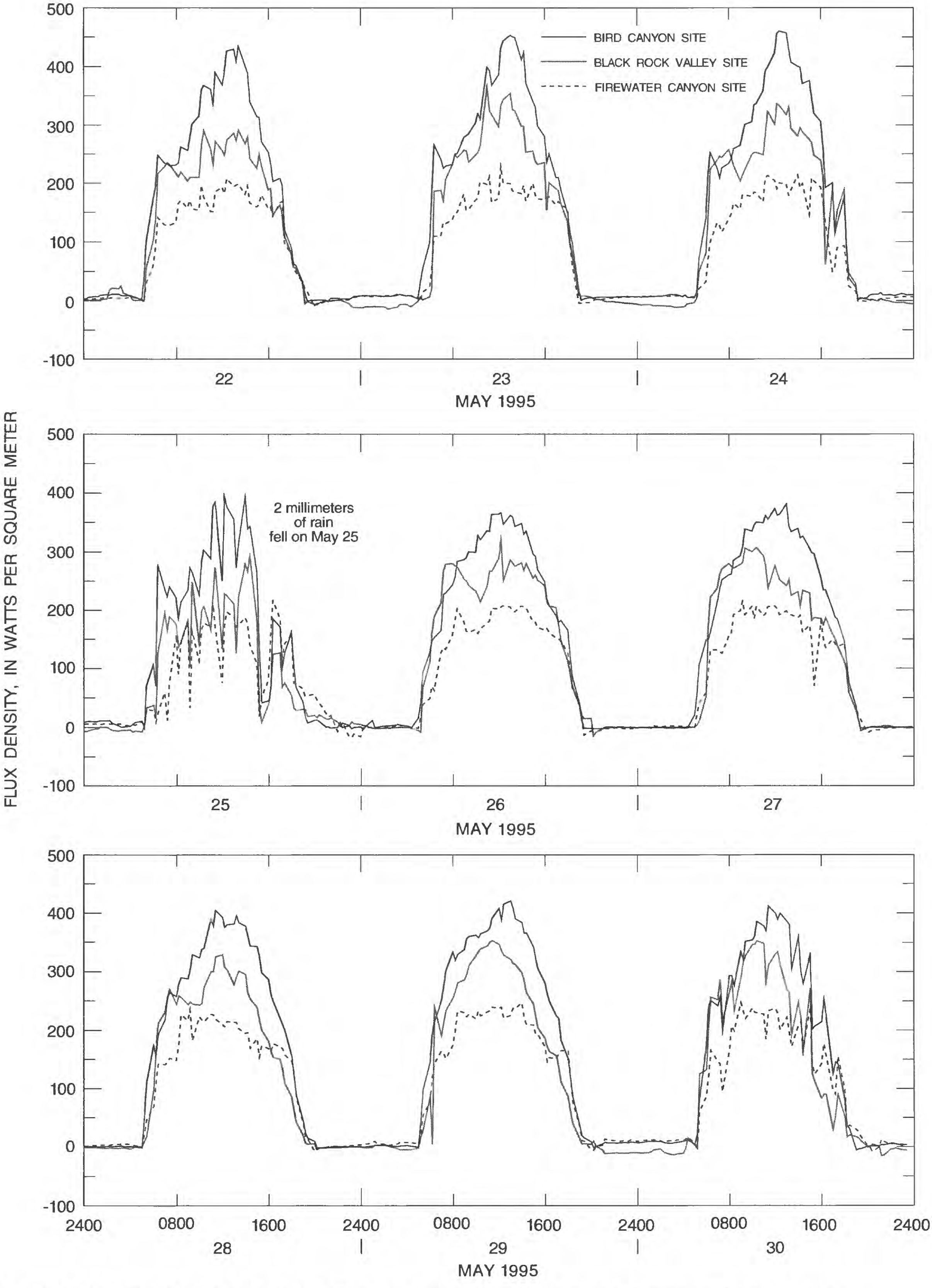


Figure 42.--Latent-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, May 22-30, 1995.

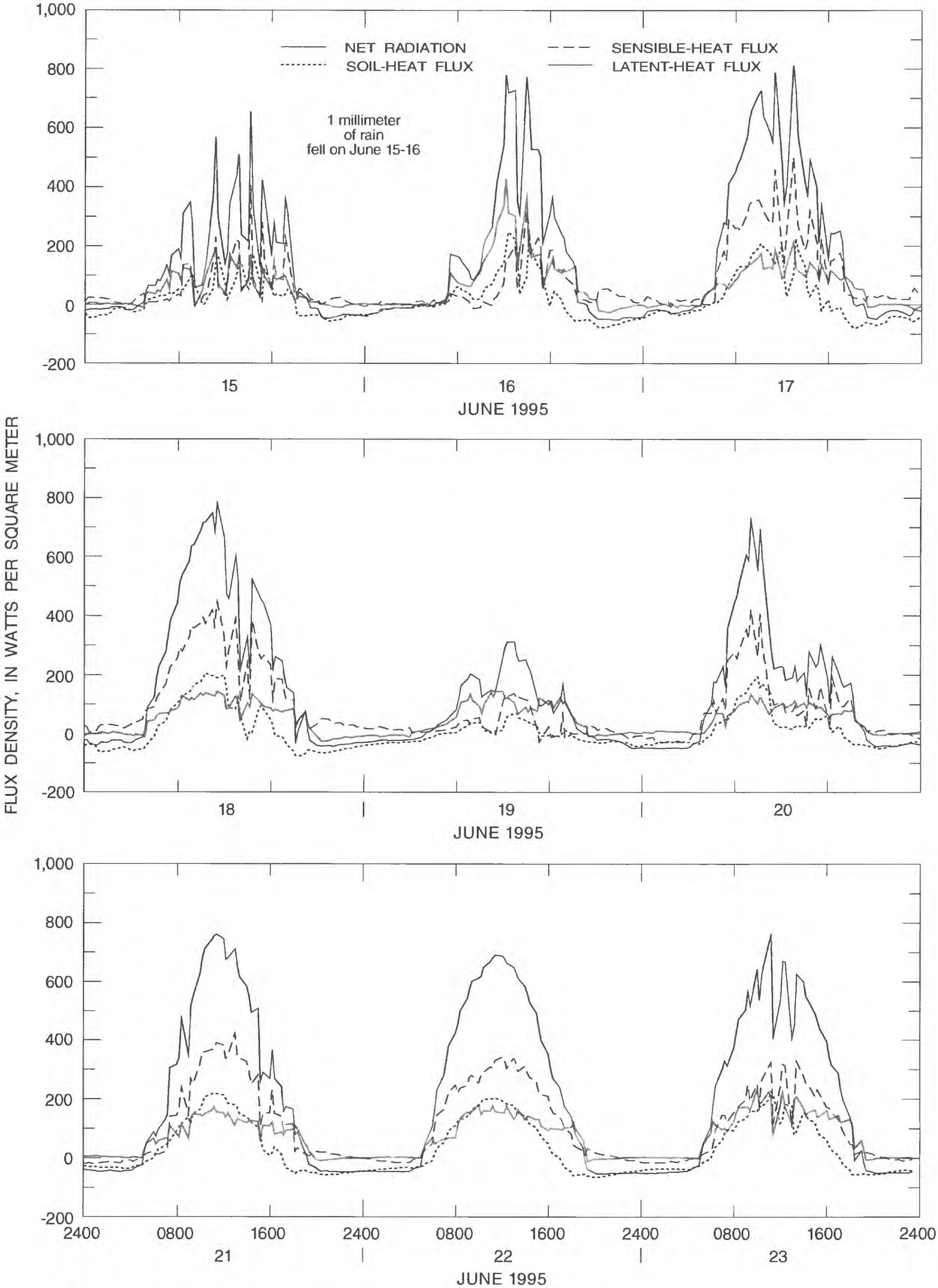


Figure 43.--Energy budget at Firewater Canyon site, June 15-23, 1995.

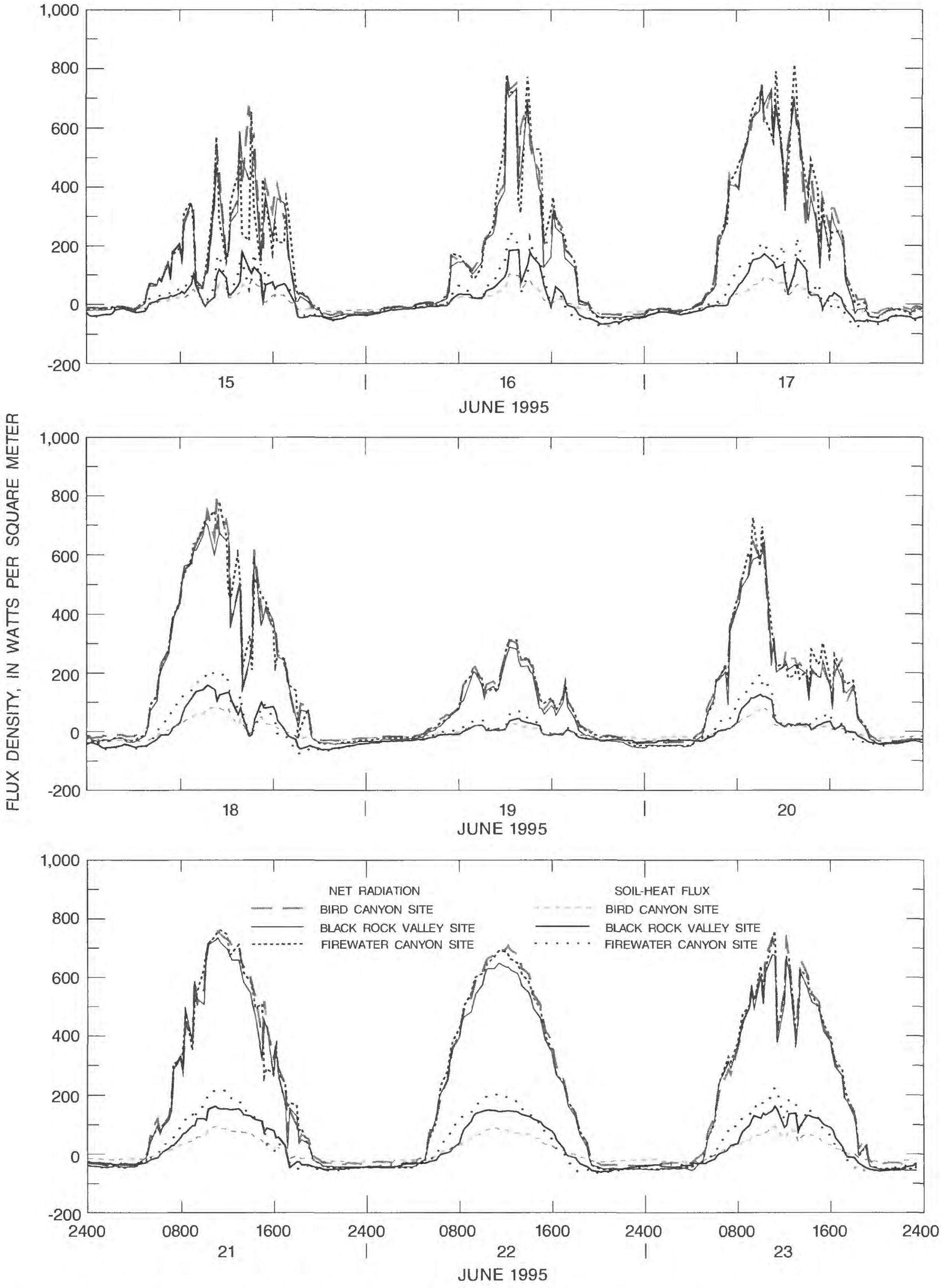


Figure 44.--Net radiation and soil-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, June 15-23, 1995.

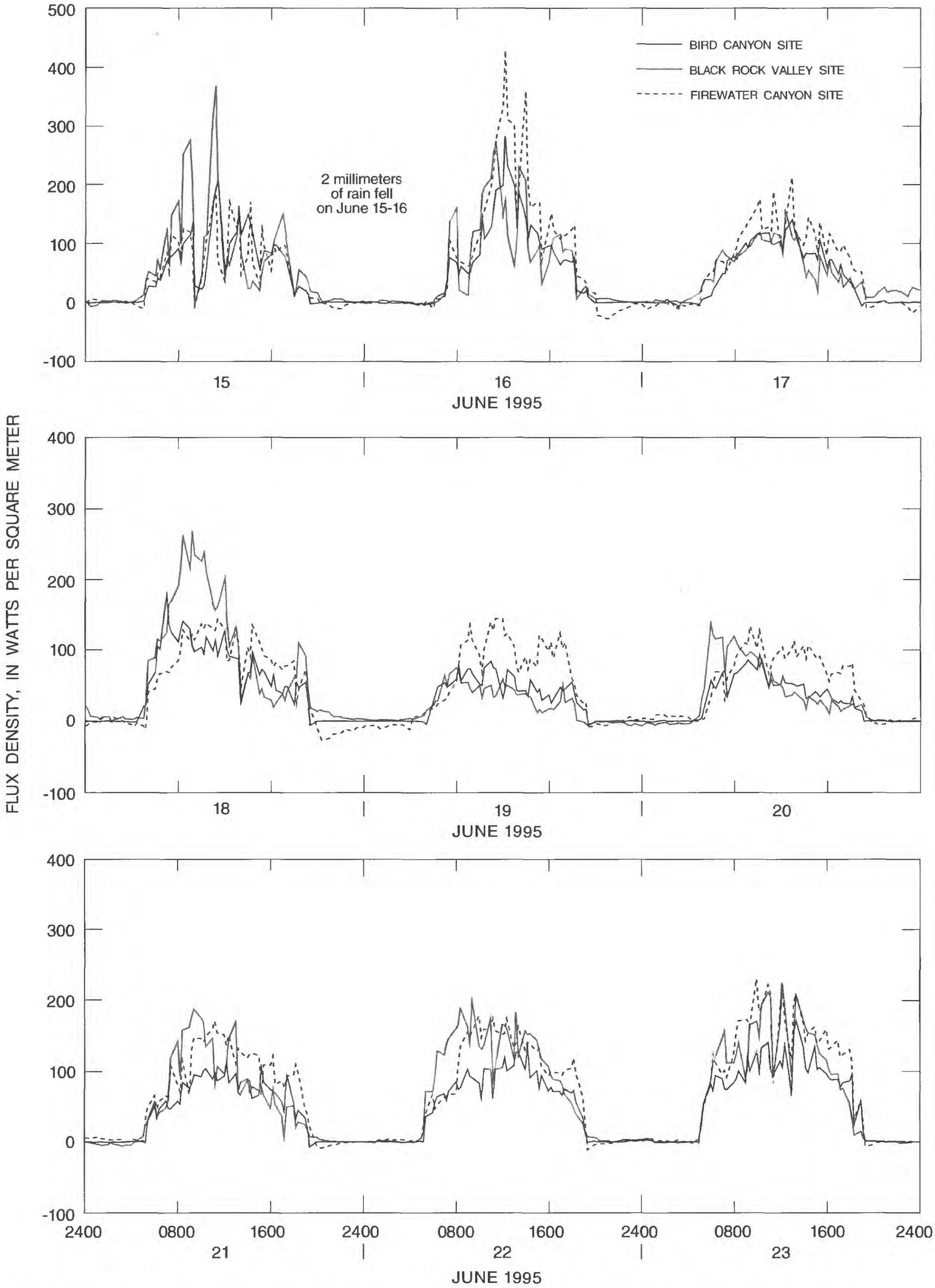


Figure 45.--Latent-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, June 15-23, 1995.

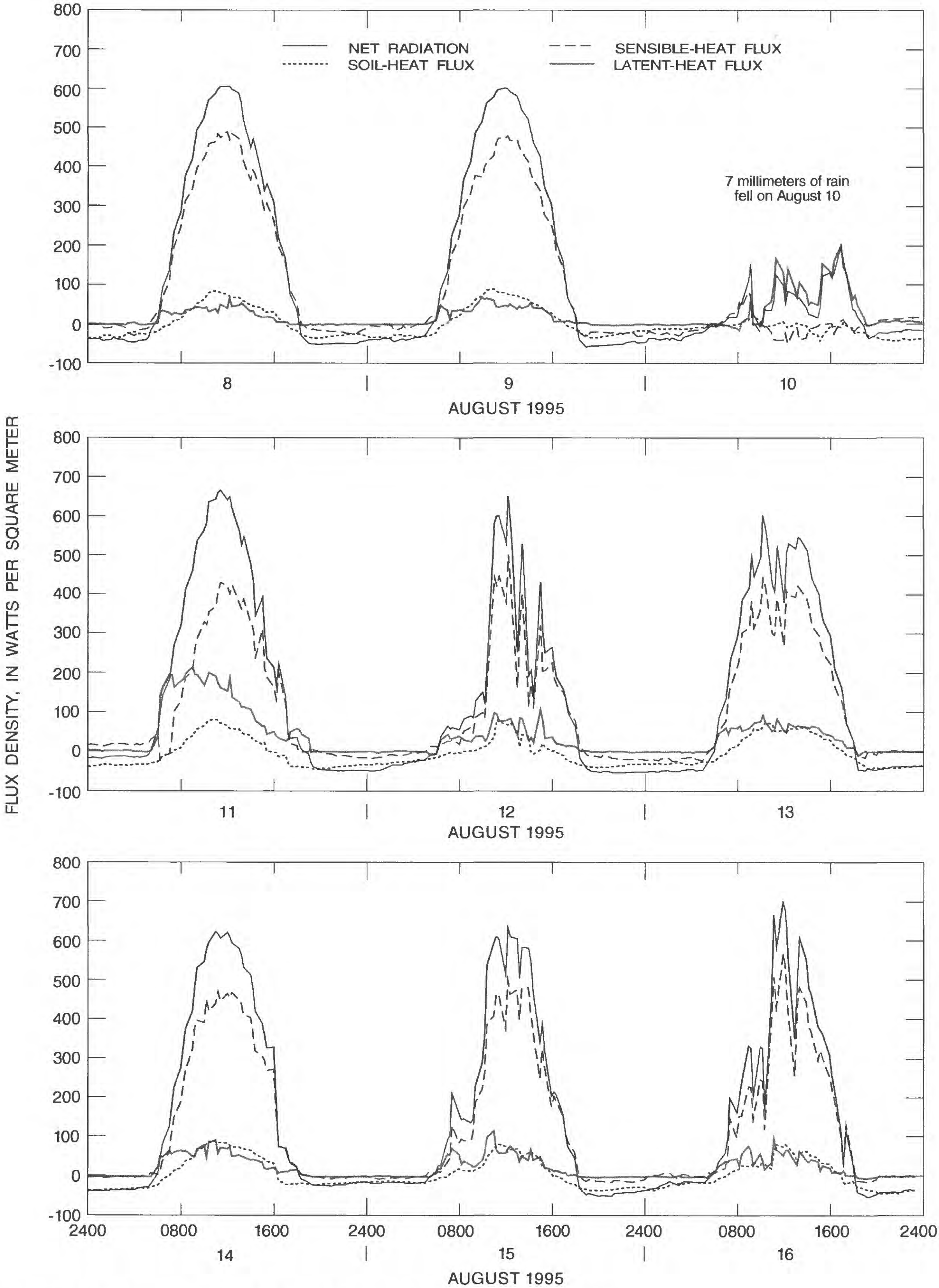


Figure 46.--Energy budget at Bird Canyon site, August 8-16, 1995.

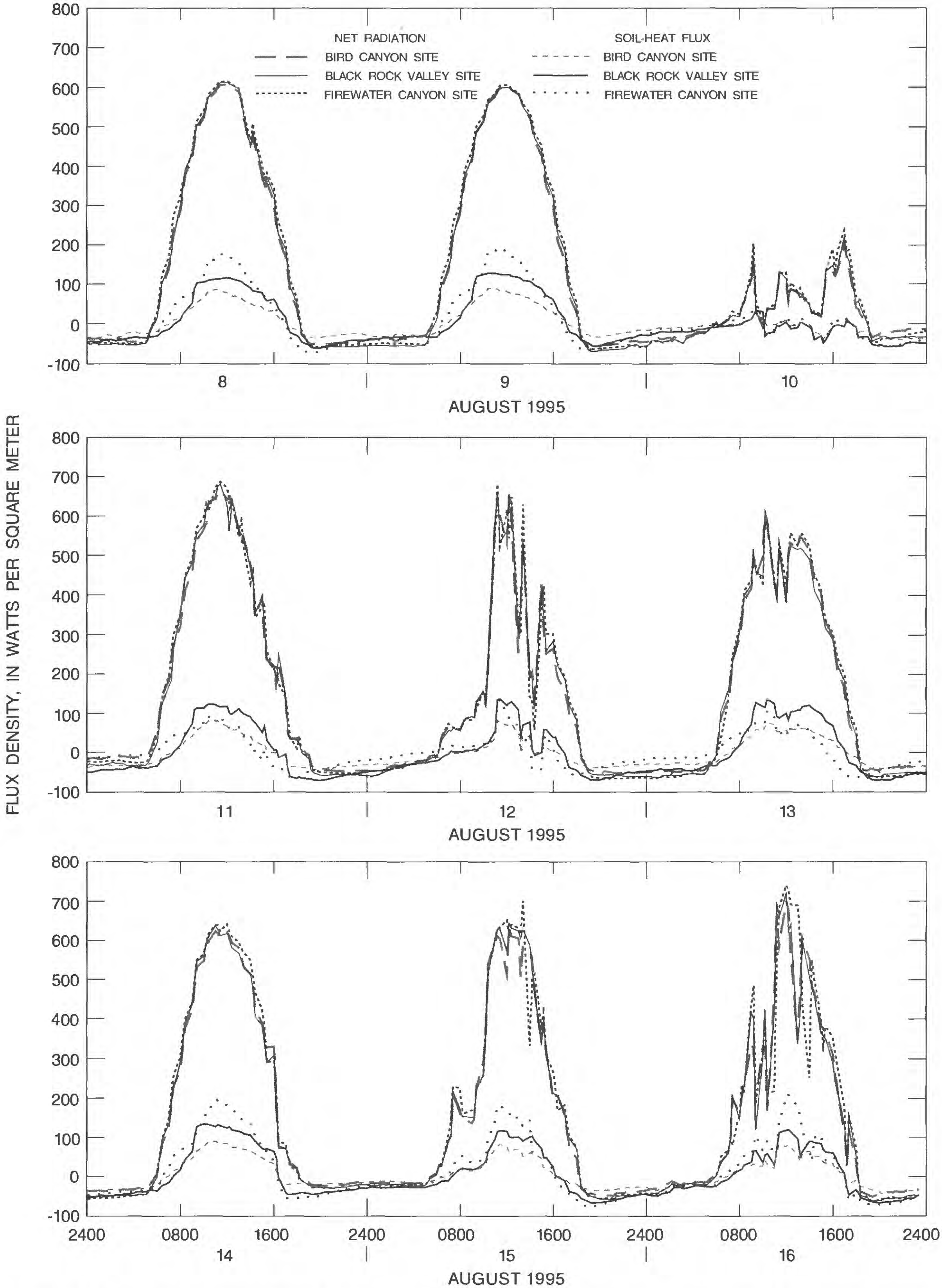


Figure 47.--Net radiation and soil-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, August 8-16, 1995.

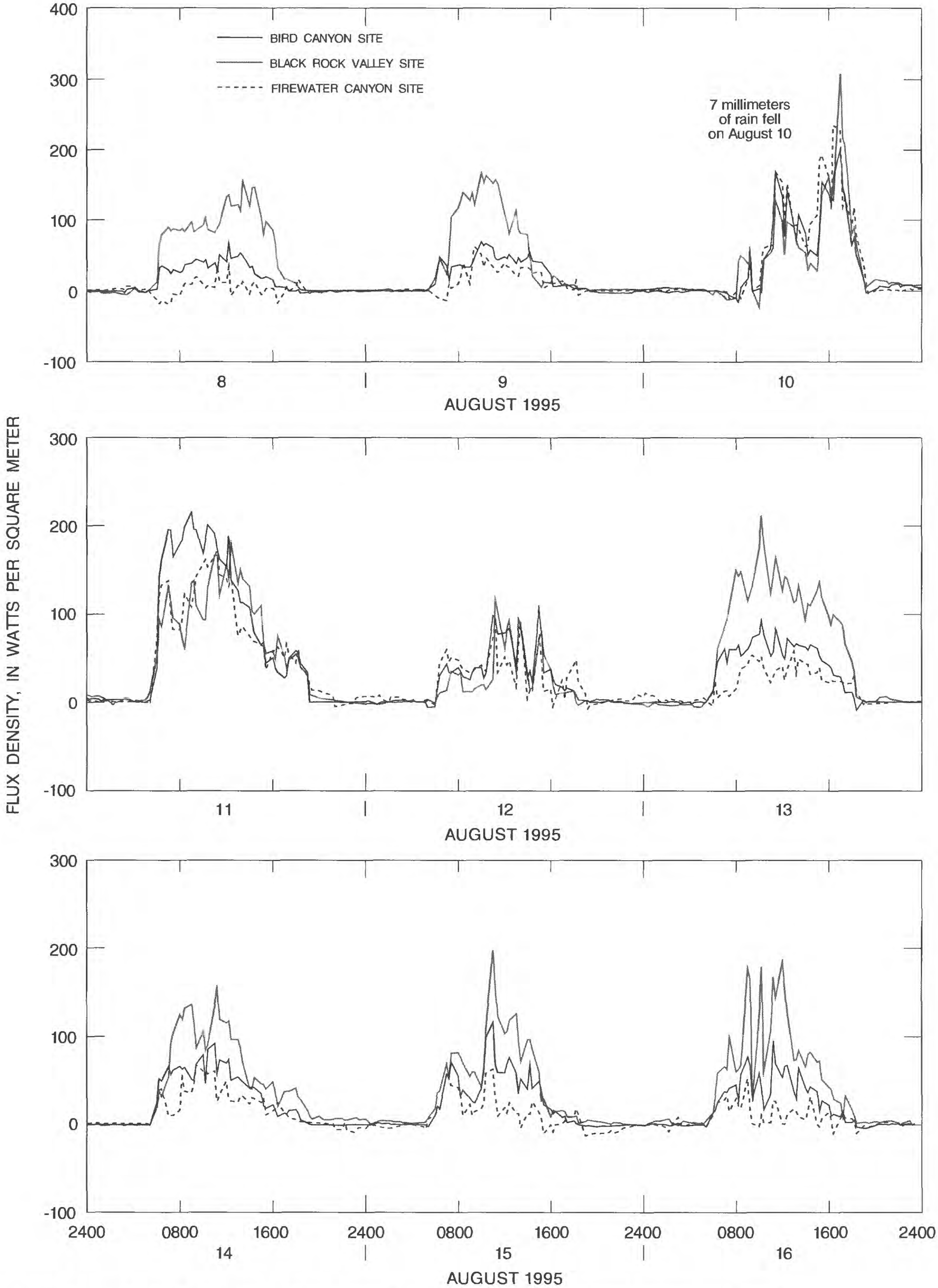


Figure 48.--Latent-heat flux at Bird Canyon, Black Rock Valley, and Firewater Canyon sites, August 8-16, 1995.

During the August 8-16 period, latent-heat flux and ET were highest at the Black Rock Valley site (fig. 48). Black Rock Valley site ET was almost 50 percent more than ET at the Bird Canyon site and over 200 percent of ET at the Firewater Canyon site. Black Rock Valley site ET averaged 1-2 mm/day—less than 1 mm/day would be expected at this time of year. These high values suggest that perhaps sagebrush roots at this site received more soil moisture than plants at the other two sites. Sagebrush roots can penetrate 4 m or more to bring additional water to the surface. Why this is not the case at the similarly vegetated Firewater Canyon site is not clear. Perhaps the different soil types at the two sites provide part of the explanation. All three sites contain silt loam soils, but only the Willis Silt Loam at the Black Rock Valley and Bird Canyon sites is known to contain a hardpan. This hardpan could be a factor to consider in soil-moisture availability in late summer. Detailed studies of the hydrogeology of this area have not been performed, so it is difficult to assess what is occurring underground. The only exceptions to these differences in latent-heat flux were on days with rain or clouds such as August 10 and 12, when latent-heat flux at all three sites matched reasonably well (fig. 48).

The energy-budget and ET comparisons for the Black Rock Valley, Bird Canyon, and Firewater Canyon sites show that some similarities and some differences exist in net radiation, soil-heat flux, latent-heat flux, and ET. Net radiation and soil-heat flux are nearly the same at all sites through the year, except that at the Bird Canyon site net radiation tends to be somewhat higher in May when grasses are at their peak growth, and soil-heat flux tends to be somewhat lower after March. Latent-heat flux and ET, on the other hand, vary greatly over the year, from being nearly the same at all sites early in the growing season in March and very similar at the time of plant senescence in June to being very high at the grass-covered Bird Canyon site in May and high at the Black Rock Valley site in August. Latent-heat flux and ET tended to be very similar at all sites on very cloudy days or days with rain.

SUMMARY

This report evaluates evapotranspiration (ET) at three sparse-canopy sites in an area locally known as the Big Flat in the Black Rock Valley of Yakima County, Washington. These sites are located in sagebrush (Black Rock Valley and Firewater Canyon sites) and grassland (Bird Canyon site) areas. The Bowen-ratio and Penman-Monteith methods were used to estimate ET at the sites. Bowen-ratio data from a fine-wire thermocouple/cooled-mirror hygrometer system (Bowen-ratio instruments) were collected for various periods from March 1992 to October 1995. Additional Bowen-ratio data from fixed-sensors (fixed-sensor instruments), which did not remove sensor bias, were collected for various periods from April 1993 to October 1995. Penman-Monteith data were collected from May 1992 to March 1993 only at the Black Rock Valley site.

ET showed a similar seasonal pattern at the study sites. Peak ET of 3-6 millimeters per day occurred in spring, during periods of maximum plant growth. Lowest ET occurred in dry periods during late summer, fall, or winter, with ET usually less than 1 millimeter per day. For the period of study at the Black Rock Valley site, March 1992 to October 1995, on average, 62 percent of the annual ET occurred from April to July, 17 percent occurred from August to October, and 21 percent occurred from November to March.

Overall, latent-heat flux and ET estimated with the Penman-Monteith method compared very well with latent-heat-flux and ET estimated with the Bowen-ratio method. The square of the correlation coefficient for Penman-Monteith daily ET, compared with Bowen-ratio daily ET, was 0.91. This high correlation coefficient results primarily because the Bowen-ratio method was used to calibrate the Penman-Monteith method for the canopy resistance—Penman-Monteith ET estimates are dependent on those from the Bowen-ratio method. However, during some periods, Penman-Monteith ET did not compare well with Bowen-ratio ET. For instance, on days with high wind speeds at night, Penman-Monteith estimates of ET were as much as 40 percent higher than those made with the Bowen-ratio method. However, part of this difference may have been due to the methods.

Most of the time, latent-heat fluxes and ET estimated with fixed-sensor instruments compared well with latent-heat fluxes and ET estimated with Bowen-ratio instruments. The square of the correlation coefficient comparing daily ET estimates was 0.86. Comparisons were best during cool, cloudy, windy, wet weather when the square of the correlation coefficient was 0.94. Perhaps sensor bias is relatively small because of diminished solar radiation effects on the measured profiles and improved ventilation of the sensors during such weather, resulting in close agreement. In this study, fixed-sensor instruments allowed the Bowen-ratio method to be used to estimate ET when Bowen-ratio instruments (usually the cooled-mirror hygrometer) failed or could not be used, such as during the winter, and thus helped produce a continuous record of daily ET for several years. However, there were times when latent-heat fluxes and ET estimated with fixed-sensor instruments did not compare well with those from Bowen-ratio instruments. During dry, sunny days in late summer, when positive latent-heat fluxes would be expected (and were observed with the Bowen-ratio instruments), latent-heat fluxes from fixed-sensor instruments were occasionally negative, possibly due to sensor bias, and therefore they did not compare well with Bowen-ratio instrument latent-heat fluxes. In extremely dry conditions, such as occurred in 1994, both Bowen-ratio and fixed-sensor instruments showed negative latent-heat fluxes much of the time, and Bowen-ratios from June 20 to October 24, 1994, had to be estimated or partly estimated using isolated intervals of data believed to represent actual conditions. On 80 percent of the days during this period, estimated daily ET was less than 0.3 millimeter.

ET and precipitation data were collected from October 1994 to October 1995 at the Bird Canyon and Firewater Canyon sites to evaluate the reliability of data collected at the Black Rock Valley site. Daily, monthly, and annual differences in ET estimates at the sites were observed between the three sites even though they are all located within 3.5 kilometers of each other. The Firewater Canyon site is located 2.5 kilometers east, and the Bird Canyon site 0.8 kilometer west of the Black Rock Valley site. Daily ET ranged from near zero during dry periods in late summer, fall, and winter, to over 4 millimeters during periods of peak plant growth in May. From October 1994 to September 1995, cumulative precipitation at all three sites varied by only 4 percent, but the Black Rock Valley and Bird Canyon sites showed almost 30 percent more cumulative ET than the Firewater Canyon site. From late October 1994 to early September 1995, cumulative ET at the Black Rock Valley, Bird Canyon, and Firewater Canyon sites was, respectively, 139 percent, 136 percent, and 97.2 percent of cumulative precipitation. For annual periods (October 1 to September 30) from 1992 to 1995 at the Black Rock Valley site, cumulative ET ranged from 133 to 175 percent of cumulative precipitation. No adjustments were made for wind effects on the tipping-bucket gages because precipitation measured by storage gages and tipping-bucket gages differed by an average of only 6 percent.

Differences in daily and monthly ET among the three sites were high. Only at the beginning of the growing season in March, and on cool, cloudy, or wet days throughout the year was ET nearly the same at the three sites. In May, ET at the Bird Canyon site was 30 percent greater than ET at the Black Rock Valley site and 60 percent greater than ET at the Firewater Canyon site. In June, ET was greatest at the Firewater Canyon site—ET at the Bird Canyon site was 20 percent less than that at the Black Rock Valley site and 30 percent less than at the Firewater Canyon site. In August, ET was greatest at the Black Rock Valley site—Black Rock Valley site ET was almost 50 percent more than that at the Bird Canyon site and over 200 percent more than at the Firewater Canyon site.

The results of this study suggest that annual precipitation and ET are nearly equal at the Firewater Canyon site (as they are for sites on the Arid Lands Ecology Reserve, about 40 kilometers away), but not at the Black Rock Valley and Bird Canyon sites. At the Black Rock Valley site, cumulative ET ranged from 133 to 175 percent of cumulative precipitation annually from 1992 to 1995. In 1995 at the Black Rock Valley and Bird Canyon sites, cumulative ET was 139 and 136 percent, respectively, of cumulative precipitation. However, at the Firewater Canyon site in 1995, cumulative ET was only 97.3 percent of cumulative precipitation. Thus, at the Black Rock Valley and Bird Canyon sites, water for ET apparently comes not only from precipitation, but also from other sources, perhaps surface runoff or ground water from upland areas of the Yakima Ridge. Because the hydrogeology of the Big Flat in the Black Rock Valley is not well known, additional studies in this area would be needed to confirm that hypothesis.

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