Evaluating Evapotranspiration for Grasslands on the Arid Lands Ecology Reserve, Benton County, and Turnbull National Wildlife Refuge, Spokane County, Washington, May 1990 to September 1991

By Stewart A. Tomlinson

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402

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CONVERSION FACTORS AND VERTICAL DATUM

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)	$9.478x10^{-4}$	British thermal unit
Energy-flux density		
watt per square meter (W/m^2)	$5.285x10^{-3}$	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
Mass		
gram (g)	$2.205x10^{-3}$	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 AND EQUATIONS

Symbols used in text:

β	Bowen ratio, unitless
C_p	Specific heat of air, equal to 1.005 joules per kilogram 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
$FX1$	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 in 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
$\Re$	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

Symbols used in text:

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, unitless

Equations used in study 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)	$G = \left(\frac{FX1 + FX2}{2}\right) + S$

Equations used in study text:

Number	Name and source or derivation	Equation
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, 1988, p. 255)	$\gamma = \frac{P \; C_p}{L \; \varepsilon}$
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)	$LE = \frac{R_n - G}{1 + \beta}$

Equations used in study text:

Number	Name and source or derivation	Equation
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)	$s = 0.6112\left[\left(\frac{17.67}{T+243.5} - \frac{17.67\ T}{(T+243.5)^2}\right) exp\left(\frac{17.67\ T}{T+243.5}\right)\right]$
17.	Aerodynamic resistance to heat (neutral conditions) (Campbell, 1977, p. 138)	$r_h = \frac{ln\left[\frac{z - d + z_h}{z_h}\right] ln\left[\frac{z - d + z_m}{z_m}\right]}{k^2\ u}$
18.	Penman equation (potential evapotranspiration) (D.I. Stannard, U.S. Geological Survey, written commun., 1990)	$LE_p = \frac{s\,(R_n - G) + \rho_a\ C_p\,(e_s - e)/r_h}{s + \gamma}$

SYMBOLS AND EQUATIONS--CONTINUED

Equations used in study text:

Number	Name and source or derivation	Equation
19.	Penman-Monteith equation (D.I. Stannard, U.S. Geological Survey, written commun., 1990)	$LE = \frac{s(R_n - G) + \rho_a C_p (e_s - e)/r_h}{s + \gamma (r_c + r_h)/r_h}$
20.	Canopy resistance (Rearrangement of eq. 19)	$r_c = \frac{r_h}{\gamma}\left(\frac{1}{LE}\left[s(R_n - G) + \{\frac{\rho_a C_p (e_s - e)}{r_h}\}\right] - s\right) - r_h$

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ABSTRACT

This report evaluates the methods for estimating evapotranspiration, the analyses of data and estimated errors, and the estimates of evapotranspiration for four grassland sites in eastern Washington. Two sites are located on the Arid Lands Ecology Reserve in Benton County: one a full-canopy grassland in Snively Basin (Snively Basin site), the other a sparse-canopy grassland adjacent to a pair of weighing lysimeters (grass lysimeter site). Two sites are located on the Turnbull National Wildlife Refuge in Spokane County: one a full-canopy grassland in a meadow (Turnbull meadow site), the other a full-canopy grassland near a marsh (Turnbull marsh site).

The periods of study and methods used at the four sites varied. Studies extended from May 1990 to September 1991 for the Snively Basin site, from April to May 1991 for the grass lysimeter site, and from May 1991 to September 1991 for both the Turnbull meadow and Turnbull marsh sites. Evapotranspiration and energy-budget fluxes were estimated with the Bowen-ratio and Penman-Monteith methods for the Snively Basin site and the Turnbull meadow site. The Bowen-ratio method was used to estimate energy-budget fluxes and ET at the grass lysimeter site. The Penman and Penman-Monteith methods were used to estimate potential and actual evapotranspiration and energy-budget fluxes for the Turnbull marsh site. Additionally, evapotranspiration was estimated for the grass lysimeter site from data collected by weighing lysimeters.

The Bowen-ratio method provided daily estimates of evapotranspiration for the Snively Basin and Turnbull meadow sites during the main parts of the growing season, March to July; daily estimates ranged from 0.5 millimeter during dry periods to more than 4 millimeters during periods of peak plant growth. For most of the August and September data from the two sites, the Bowen-ratio method could not be used because of atmospheric conditions that resulted in invalid vapor-pressure data.

The Bowen-ratio method estimated about 41 percent of the evapotranspiration measured by weighing lysimeters at the grass lysimeter site for April and May 1991. The primary factors that might account for this difference include (1) instrumentation errors; (2) possible advection effects on the air-temperature and vapor-pressure gradients induced by the complex terrain surrounding the site; and (3) weighing lysimeter vegetation and soil monoliths not representative of the overall landscape.

For the Snively Basin and Turnbull meadow sites, the Penman-Monteith method estimated daily evapotranspiration that differed less than 35 percent from estimates made with the Bowen-ratio method. For estimates of monthly evapotranspiration, the two methods differed by less than 3 percent. Latent-heat fluxes calculated with the Bowen-ratio method were used to calibrate the Penman-Monteith equation for the canopy resistance. Then, daily average canopy resistances were calculated and used in the Penman-Monteith equation to estimate daily evapotranspiration for the entire periods of study at each site.

Evapotranspiration at the Turnbull marsh site averaged 65 percent higher than at the Turnbull meadow site for May to September 1991. This was due to moister soil at the Turnbull marsh site which averaged twice as much water content as the Turnbull meadow site for the same period. The Penman method estimated potential evapotranspiration for the Turnbull marsh site. Canopy resistance estimates at the Turnbull marsh site were based on a relation between soil moisture and canopy resistance developed for the Turnbull meadow site. These resistances were used in the Penman-Monteith equation to estimate actual evapotranspiration for the Turnbull marsh site.

For the Snively Basin site, a water budget indicated that all the precipitation received between August 20, 1990, and September 30, 1991, returned to the atmosphere as evapotranspiration. These dates reflect times when the water-storage change and evapotranspiration were near zero. The water budget included precipitation data, estimates of snow, dew, and trace precipitation, and Penman-Monteith estimates of evapotranspiration. The

water budget also indicated that some water from late summer precipitation events, occurring after the grasses had perished or gone dormant for the season, remained in the soil profile until the following spring, when it was transpired by plants. The Snively Basin site water budget showed that 16 percent of the evapotranspiration occurred from October to February, whereas 76 percent occurred from March to July. April accounted for more than 25 percent of evapotranspiration for the water-budget period. Water budgets could not be formulated for the other sites because of the short periods of study.

INTRODUCTION

Most of the precipitation that falls on grasslands in semiarid eastern Washington returns to the atmosphere as evapotranspiration (ET). ET, the quantity of water evaporated from soil and other surfaces plus the quantity 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). State and local government agencies and private citizens use ground-water recharge estimates to determine the amount of water available for agricultural and municipal supplies or other uses.

Background

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

In order to better estimate ET in eastern Washington, an ET measurement project was established in August 1989 by the U.S. Geological Survey and the Washington State Department of Ecology—new ET projects were established in 1990 and 1991 by the two agencies. The objectives of these projects were to make long-term estimates of ET for several sites in eastern Washington and to investigate a method of estimating ET requiring only standard meteorological, or easily collected, data.

Purpose and Scope

This report describes the first and second phases of a study on ET for grasslands in eastern Washington. This report presents results of ET research at four grassland sites in eastern Washington: two on the Arid Lands Ecology (ALE) Reserve near Richland and two on the Turnbull National Wildlife Refuge (NWR) near Cheney. The ALE Reserve sites were in (1) a full-canopy grassland in Snively Basin (Snively Basin site) and (2) a sparse-canopy grassland near the base of an alluvial fan adjacent to two weighing lysimeters (grass lysimeter site). The Turnbull NWR sites were in (1) a meadow-steppe grassland (Turnbull meadow site) and (2) a marsh grassland (Turnbull marsh site). This report evaluates ET analyses made at the four sites for various periods in 1990 and 1991. Also, the report compares methods used to calculate ET and discusses the differences between them. A previous report (Tomlinson, 1994) describes only the first phase and focuses on methods, instrumentation, and preliminary results for estimating ET from the Snively Basin site.

This report describes the methods, instrumentation, results, and error sources for this study. The grassland sites at Snively Basin on the ALE Reserve and the Turnbull NWR generally provided suitable conditions for using energy-budget methods of estimating ET because of their uniform canopy height, flat to gently sloping aspect, and extensive cover in their respective areas. The sparse-canopy grass site on the ALE Reserve was chosen because of its proximity to weighing lysimeters.

Acknowledgments

The author thanks Battelle, Pacific Northwest Laboratories for their assistance in obtaining permission to install ET instrumentation on the ALE Reserve and for providing data collected from weighing lysimeters on the ALE Reserve. The author also thanks the U.S. Fish and Wildlife Service for assistance in obtaining required permits and in selecting sites for instrumentation on the Turnbull NWR.

Description of the Study Areas

The Snively Basin and grass lysimeter sites are located in the Rattlesnake Hills on the ALE Reserve of the Hanford Site (also called Hanford Works, Hanford Reservation, and Hanford) in western Benton County, Wash., about 64 kilometers east of Yakima and 40 kilometers west of Richland (fig. 1). The Snively Basin site's altitude is 494 meters. The grass lysimeter site is located on the base of an alluvial fan, adjacent to two weighing lysimeters, 5 kilometers northeast of the Snively Basin site, at an altitude of 293 meters.

The ALE Reserve encompasses diverse topography, with altitudes ranging from about 134 meters in the lower valleys to 1,073 meters at the crest of the Rattlesnake Hills. Dominant physiographic features of the surrounding area are the Columbia River to the north and east, the Yakima River to the south, and the Cascade Range about 160 kilometers to the west.

The Turnbull meadow and Turnbull marsh sites are located on the Turnbull NWR about 7 kilometers southeast of Cheney, Wash. (fig. 1). The Turnbull meadow site is located in a grassy meadow at an altitude of 706 meters. The Turnbull marsh site is located on a grassy knoll at an altitude of 696 meters in a marshy area of seasonal wetlands.

The Turnbull NWR topography is flat to gently sloping with little variation from an altitude of about 700 meters. Many permanent and seasonal lakes and ponds dot the Refuge. Major physiographic features of the surrounding area are the Palouse Hills, about 10 kilometers south and west, and the Spokane River, about 50 kilometers north.

Climate

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

Precipitation on the ALE Reserve from 1969 through 1980 ranged from about 165 millimeters per year in the lower altitudes to more than 280 millimeters annually just north of the Rattlesnake Hills crest (Stone and others, 1983). The Snively Basin site is located in one of the wettest areas of the ALE Reserve. Based on an average of three precipitation stations close to the Snively Basin study site (Stone and others, 1983), the estimated annual precipitation averages about 245 millimeters. For the grass lysimeter site, estimated annual precipitation averages about 209 millimeters, based on an average of two nearby stations reported by Stone and others (1983). More than 75 percent of the precipitation on the ALE Reserve falls from October through April, about one-fourth of it as snow. June through September is normally the driest time of year, although convective storms during this period can account for as much as 20 percent of the annual precipitation.

Annual precipitation at the Turnbull NWR has not been determined, but it is assumed to be similar to that at Cheney, only 7 kilometers away. Annual precipitation at Cheney was measured from 1938 to 1955 and averaged 491 millimeters (Maytin and Gilkeson, 1962). Annual precipitation at other nearby stations averaged 373 millimeters at Sprague (Maytin and Gilkeson, 1962), 30 kilometers west, and 411 millimeters at Spokane (Ruffner and Bair, 1987), 48 kilometers northeast. As at the ALE Reserve, more than 75 percent of the precipitation falls from October through April, with one-fourth to one-third in the form of snow. July through September is usually the driest period of the year. Occasional thunderstorms, most often from May through September, can provide as much as 10 percent of the annual precipitation.

Dew adds to precipitation at all sites. Monteith (1963b) estimated that water input from dewfall can range from 10 to 40 millimeters annually in some climates. No measurements have been made of dew on the ALE Reserve or the Turnbull NWR. However, Rickard and others (1988) estimate dew at less than 5 percent of the annual precipitation on the ALE Reserve, based on available meteorological data.

Temperatures at all sites are primarily continental (affected mostly by dry air masses from the interior of the North American continent), but frequent storm fronts move in from the Pacific Ocean, mainly during the winter months, moderating temperatures and bringing precipitation. For the weather station nearest to the ALE Reserve sites, located at Hanford (meteorologial station), about 21 kilometers away from the Snively Basin site, annual temperatures average 11.7 degrees Celsius. Temperature extremes at Hanford range from 46 to -33 degrees Celsius. At Cheney, 7 kilometers from the Turnbull NWR sites, the average annual temperature is 8.7 degrees Celsius. Temperature extremes at Cheney range from 42 to -37 degrees Celsius.

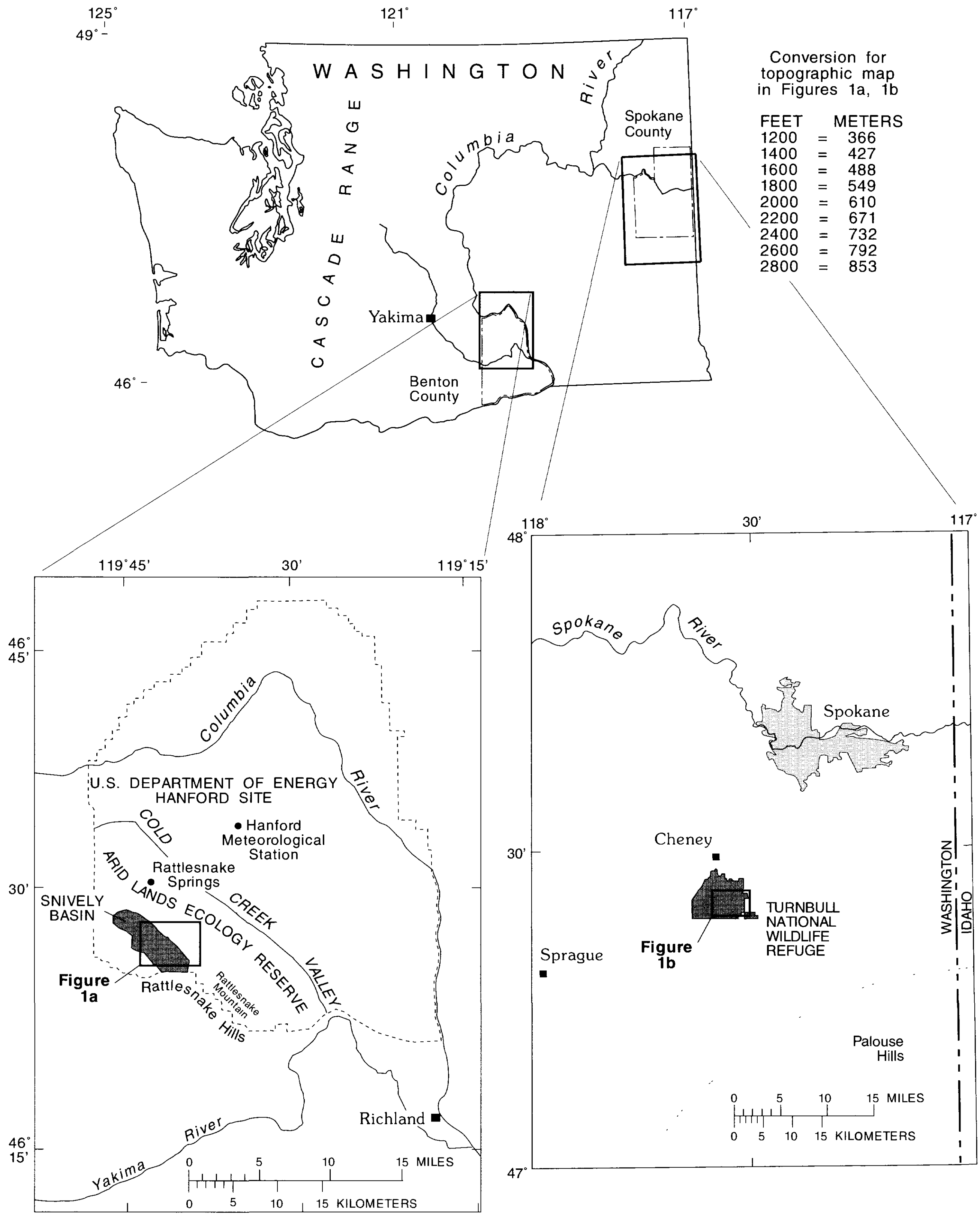

Figure 1.--Location of evapotranspiration study sites in the Arid Lands Ecology Reserve and the Turnbull National Wildlife Refuge.

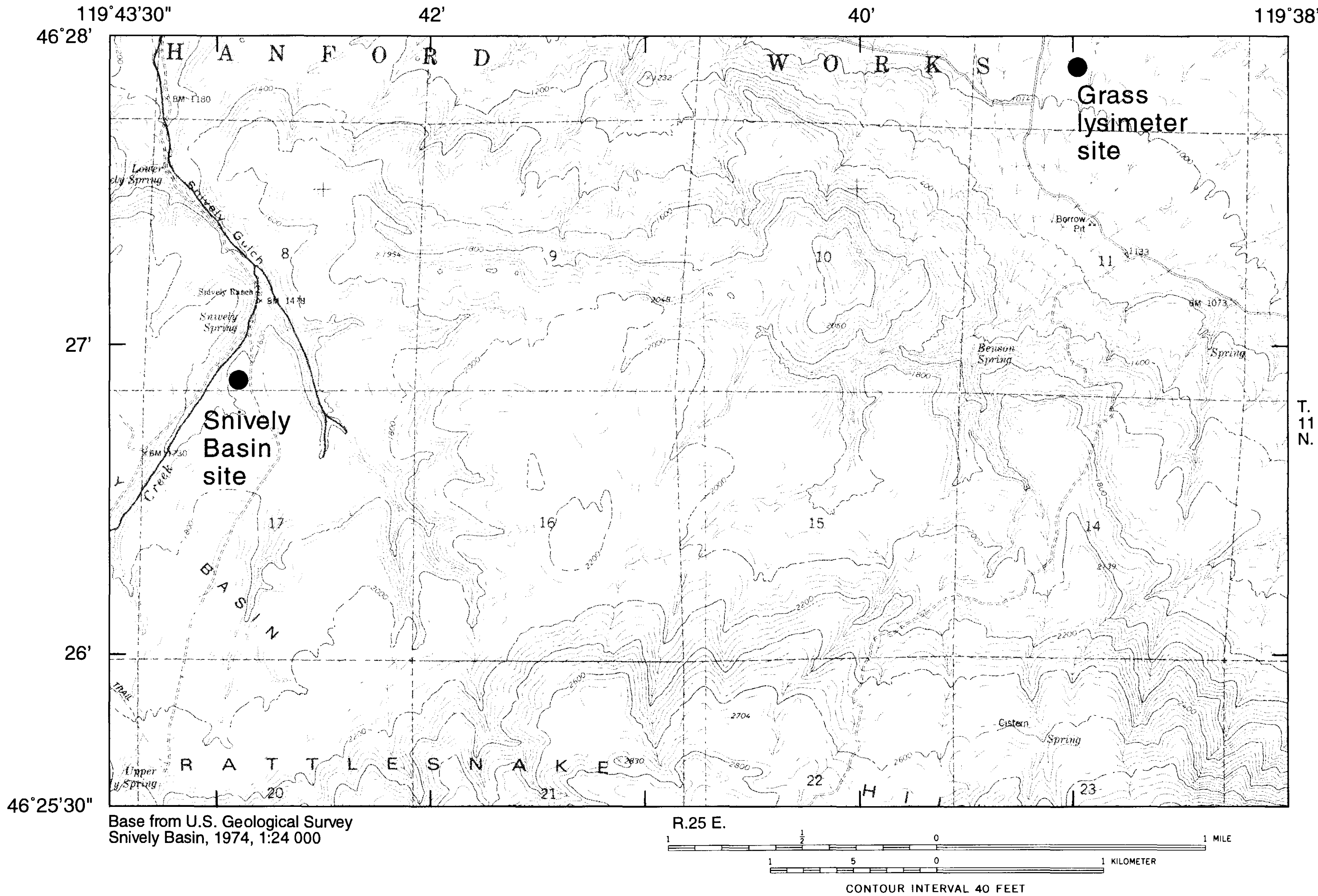

Figure 1a.--Location of Snively Basin site and grass lysimeter site.

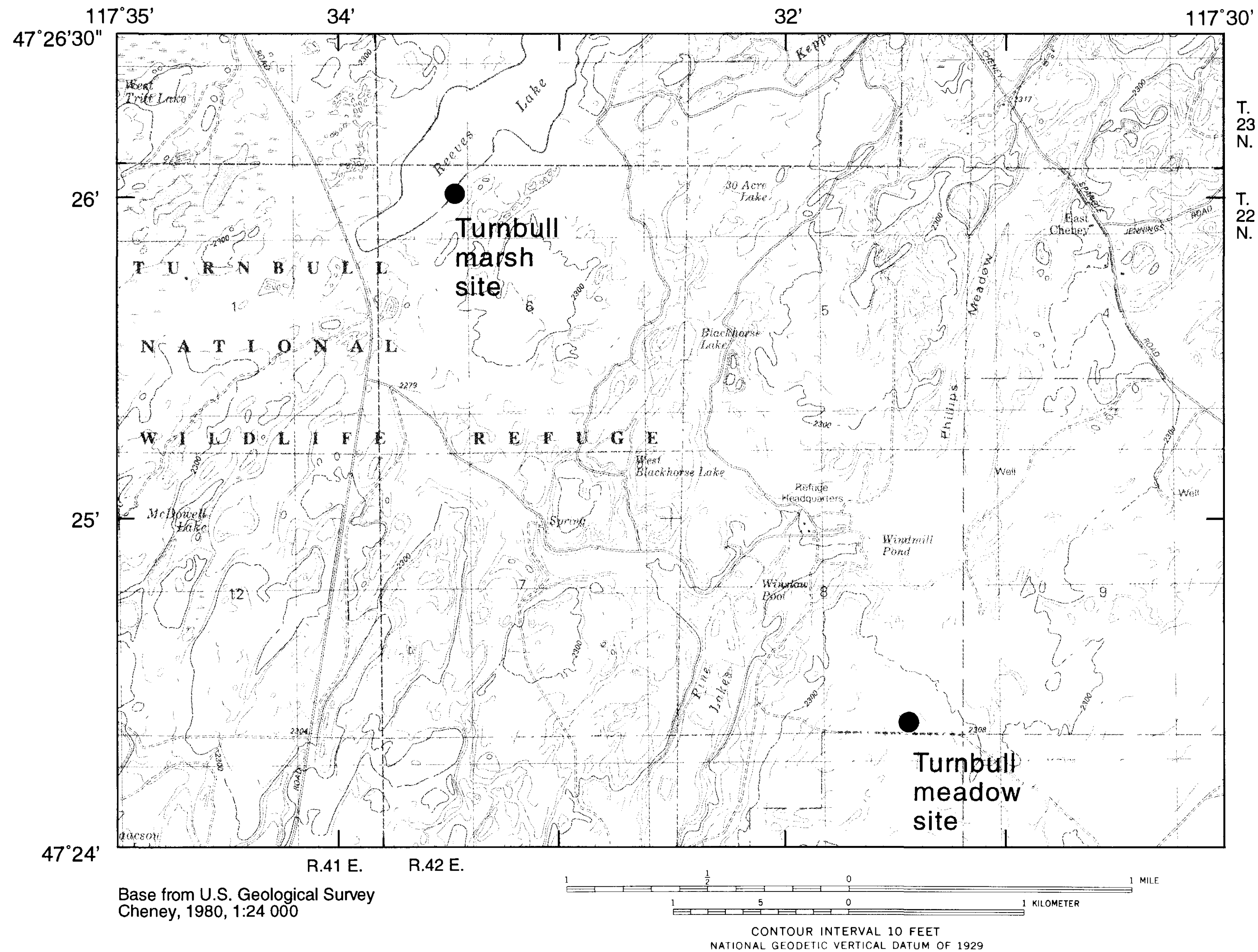

Figure 1b.--Location of Turnbull meadow and Turnbull marsh sites.

Vegetation

All study sites are located in grasslands. The sites on the ALE Reserve have a cover composed of cheatgrass (*Bromus tectorum*), bluebunch wheatgrass (*Agropyron spicatum*), and Sandbergs bluegrass (*Poa sandbergii*). Cheatgrass, an invasive grass from Europe introduced to Washington about 1890 (Franklin and Dyrness, 1988), predominates at the Snively Basin site. Bluebunch wheatgrass and Sandbergs bluegrass predominate at the grass lysimeter site. Vegetation covers about 80 to 100 percent of the Snively Basin site and 25 to 60 percent of the grass lysimeter site. The height of the grassland canopy is about 0.35 meter at the Snively Basin site and 0.25 meter at the grass lysimeter site. At the Snively Basin site, roots from the grasses extend into the soil about 0.20 meter, though some roots extend as deep as 1.1 meters. Franklin and Dyrness (1988) found that cheatgrass roots penetrate as deep as 0.97 meter.

Other plants occurring in small numbers with the grasses on the ALE Reserve are rabbitbrush (*Chrysothamnus nauseouses*), bitterbrush (*Purshia tridentata*), and other annuals and perennials. Sagebrush (Artemesia tridentata) is rare at both ALE study sites, though it does occur extensively in areas about 200 meters away. Sagebrush is a fire-sensitive species (Franklin and Dyrness, 1988) and a major fire in 1984, which burned 80 percent of the ALE Reserve (Rickard and others, 1988), eliminated sagebrush at both ALE Reserve study sites.

Riparian vegetation occupies small areas adjacent to springs on the ALE Reserve. Areas such as Snively Gulch contain small numbers of woody plants, including trees. These trees include black cottonwood (*Populus trichocarpa*), common chokecherry (*Prunus virginiana*), Columbia hawthorne (*Crataegus columbiana*), several species of willow (*Salix species*), and a naturalized exotic, white poplar (*Populus alba*). Riparian plant identification was aided by Hayes and Garrison's "Key to Important Woody Plants of Eastern Washington" (Hayes and Garrison, 1960). The trees closest to the grass lysimeter site are several naturalized Siberian elms (*Ulmus pumila*) at the site of an abandoned ranch, about 3.2 kilometers away.

At the ALE Reserve sites, grassland vegetation grows most rapidly during the wet winter and spring seasons. Growth is at its peak from March through May, when evapotranspiration is also expected to be at its maximum because of the transpiration from the growing vegetation. Drier summer weather, beginning in June, slows growth and ultimately causes the grasses to seed and perish or go dormant. Growth begins again in late summer or fall following the first major precipitation.

The Turnbull meadow site is located in an area of meadow steppe dominated by perennial grasses. Predominant species are Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass (*Agropyron spicatum*), Merrills bluegrass (*Poa ampla*), Sandbergs bluegrass (*Poa sandbergii*), and Kentucky bluegrass (*Poa pratensis*). Mixed with the grasses are an abundance of other annual and perennial plants such as silky lupine (*Lupinus sericeus*), western yarrow (*Achillea millefolium*), and sticky geranium (*Geranium viscosissimum*). Vegetative cover is thick and lush and the canopy averages 0.91 meter high.

The Turnbull marsh site is located in a mixed grass community on a peninsular knoll bordered by seasonal water on three sides. The knoll rises about 3 meters above the bed of the seasonal wetland and is about 4.5 meters wide and 9 meters long. The vegetation, a mixture of grasses, includes wheatgrass (*Agropyron species*) and ryegrass (*Lolium species*). Other vegetation includes bulrushes (*Scirpus species*), sedges (*Carex species*), common rush (*Juncus effuses*), common cat-tail (*Typha latifolia*), and common thistle (*Cirsium vulgare*). Vegetation is dense and averages 0.61 meter high.

A variety of trees and shrubs also grow on the Turnbull NWR. Thickets of round-leaved snowberry (*Symphoricarpos albus*) grow near both study sites. The predominant tree in the drier areas is ponderosa pine (*Pinus ponderosa*). Creeks in the area support other trees such as quaking aspen (*Populus tremuloides*) and common chokecherry (*Prunus virginiana*). A great variety of other plant life grows on the Turnbull NWR (U.S. Fish and Wildlife Service, 1991).

Most vegetation at the Turnbull NWR sites remains dormant during the winter because of cold weather. The grasses probably begin growth at the Turnbull meadow site in March or April with maximum growth from May through mid-July. Dry summer weather from late July through September slowly causes the vegetation to seed and go dormant or perish. At the Turnbull marsh site, plant growth probably also begins in April; however, the water table remains high enough so that most vegetation remains moderately active into September. Freezing temperatures usually begin in September or October, causing vegetation remaining in growth to go dormant or perish.

Soils and Geology

All study sites are located in the Columbia Plateau geologic province. The major geologic features of this area are numerous layers of basalt, the result of lava flows during the Miocene and Pliocene eras, and silt, gravel, and 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 period (Alt and others, 1984). Wind-blown loess and volcanic ash were also deposited on the Plateau during various periods of geologic history.

The ALE Reserve lies on the north side of the Rattlesnake Hills within the Pasco Basin. Loess, fine-grained sand, and layers of volcanic ash cover the ALE Reserve (Rockwell International, 1979). Bedrock is composed of basalt.

Ritzville silt loam, a dark grayish-brown soil that develops under grassland from silty windblown deposits mixed with a small amount of volcanic ash, predominates in the Snively Basin study area (Hajek, 1966). The Ritzville silt loam is generally greater than 1.5 meters thick and has high water-holding capacity, moderate permeability, and low runoff potential (U.S. Department of Agriculture Soil Survey Report, 1971).

Warden silt loam is found at the grass lysimeter site. This soil differs from the Ritzville silt loam in that Warden becomes strongly calcareous at about 0.5 meter. Granitic boulders are found in many areas with Warden silt loam. These boulders were carried to the area by the glacial ice of the Spokane Flood. Hajek (1966) reported that Warden soils intergrade to Ritzville soils at an altitude of approximately 366 meters.

The Turnbull NWR is located along the eastern margin of the Columbia Plateau in an area called the Channeled Scablands (Olson and others, 1975). This area was one of the major watercourses of the Spokane Flood (Alt and Hyndman, 1984), and heavy scouring of the basalt bedrock by the flood created many various-sized basins that are the present-day potholes, ponds, and lakes in the area. The most common orientation of these features is in a southwest to northeast alignment, parallel with the main direction of the Spokane Flood. Bedrock is basalt.

The Turnbull meadow site is covered by Hesseltine silt loam. This soil developed from gravelly glacial outwash overlain by a thin mantle of loess (Maytin and Gilkeson, 1962). It occupies nearly level to gently sloping areas and basalt bedrock is usually about 0.3 meter below the surface.

The peninsular knoll on which the Turnbull marsh site is located was constructed in the 1960's and is probably a mixture of several soil types, but from samples taken from the top 0.2 meter of the soil profile, Saltese muck appears to be the major soil type. The Saltese muck was formed from aquatic plants in areas having a high water table (Maytin and Gilkeson, 1962). The upper 0.5 meter is a black, granular, permeable muck. Underneath are reddish-brown layers of raw peat derived from tules, reeds, and sedges.

Hydrology

At all study sites, most precipitation that falls is lost to ET. For the sites on the ALE Reserve, little water penetrates more than a few meters below the surface except during wet periods in winter, when ET is minimal. In a water-balance study for a sandy soil on the Hanford Site, Gee and Kirkham (1984) reported that 5 centimeters of water penetrated 3.5 meters below the land surface in wet years. Link and others (1990) found that grass-covered areas of the ALE Reserve held more water at depths of 2.75 meters than areas covered with sagebrush. Consequently, grass-covered areas, such as both ALE study sites, would likely have more recharge than areas covered with the deeper-rooted sagebrush, which would remove deeper soil moisture.

Schwab and others (1979) described 125 springs in the area and found flows ranging from small seeps with instantaneous discharges estimated at less than 1.6×10^{-5} cubic meters per second (one-quarter gallon per minute) to streams originating from multiple springs with combined flows of 4.4×10^{-3} cubic meters per second (70 gallons per minute). Composed of discharge from these springs and of seasonal snowmelt from higher altitudes, streams flow down to the lower altitude of the Reserve, where they disappear along losing reaches. In so doing, the streams recharge a perched water table, which is about 30 meters above the true static water table (Harr and Price, 1972).

The largest spring in the Snively Basin is Lower Snively Spring, with an estimated flow of about 2.8×10^{-3} cubic meters per second (45 gallons per minute; Schwab and others, 1979). The gaining reaches of the channel fed by Snively Spring represent the primary surface runoff in Snively Basin except during and shortly after intense rainfall.

The spring closest to the grass lysimeter site is Benson Spring. It is located 2 kilometers south of the site and flows at an estimated 6.2×10^{-4} cubic meters per second (10 gallons per minute; (Schwab and others, 1979).

At the Turnbull NWR, some ground-water recharge probably occurs most years, though timing and amount are variable. In a study of southern Spokane County, Olson and others (1975) estimated that about 2 to 3 percent of the annual precipitation reaches aquifers. Recharge is mainly through infiltration along stream channels and wetlands in the area.

From November through March, at the Turnbull NWR, ET rates are low (because of the cold weather), while precipitation is at its highest for the year. This combination recharges soil and ground-water systems while seasonal basins and lakes are refilled and wetlands are reflooded. Some precipitation may become overland runoff during heavy rain or when rain falls on frozen ground. The recharged water begins to be lost significantly to ET from about April to July. By August or September, the lakes and wetlands have much lower water levels or, in some cases, have become dry. The quantity of water loss varies from year to year, depending on precipitation, air temperature, solar radiation and other meteorological factors. Autumn rains usually start in October, beginning the annual hydrologic cycle again.

EVAPOTRANSPIRATION METHODS

To estimate ET using energy-budget methods, instrumentation collected data on net radiation, solar radiation, wind speed, air temperature, vapor pressure, relative humidity, soil temperature, soil-heat flux, and precipitation. Field personnel collected soil samples during site visits; laboratory analysis of these samples determined soil-water content. Net radiation, air temperature at two heights, vapor pressure at two heights, soil temperature, soil-heat flux, and soil-water content were required to estimate ET using the Bowen-ratio method. Net radiation, wind speed, air temperature, relative humidity, soil temperature, soil-heat flux, and soil-water content were required to estimate potential ET with the Penman method and actual ET with the Penman-Monteith method. Precipitation and solar radiation data were not required for either method; they were collected for use in interpreting the other data.

For the Snively Basin sites, data were collected from May 30, 1990, to September 30, 1991, and ET was estimated with the Bowen-ratio and Penman-Monteith methods. For the grass lysimeter site, data were collected from April 1, 1991, to May 14, 1991, and ET was estimated with the Bowen-ratio method. Also, at this site, ET was estimated from weight data collected by two weighing lysimeters operated and maintained by Battelle, Pacific Northwest Laboratories for the U.S. Department of Energy. For the two sites on the Turnbull NWR, data were collected from May 15, 1991, to September 30, 1991. For the Turnbull meadow site, ET was estimated using the Bowen-ratio and Penman-Monteith methods. For the Turnbull marsh site, potential ET was estimated using the Penman method and actual ET was estimated using the Penman-Monteith method.

Instrumentation

Figure 2 shows the instrumentation used to collect data to calculate ET at the four grassland sites. Table 1 describes each of the instruments. More detailed information is presented by Tomlinson (1994). Two sets of instrumentation collected data at the Snively Basin, grass lysimeter, and the Turnbull meadow sites (fig. 2). One set of this instrumentation collected the data necessary for the Bowen-ratio method. The second set of instrumentation collected the data necessary for the Penman-Monteith method. Only Penman-Monteith instrumentation collected data at the Turnbull marsh site.

The Bowen-ratio instrumentation included one data logger, one net radiometer, one set of four averaging soil-temperature thermocouples, two soil-heat-flux transducers, one cooled-mirror hygrometer with two vapor-pressure intakes, and two fine-wire thermocouples for measuring air temperature. The Penman-Monteith instrumentation included one data logger, one net radiometer, one pyranometer, one anemometer, one temperature and relative-humidity probe, one precipitation gage, one set of four averaging soil-temperature thermocouples, and two soil-heat-flux transducers. Additionally, personnel collected soil moisture samples at all four sites in order to estimate the soil-heat storage term for Bowen-ratio and Penman-Monteith methods. Each set of instrumentation was mounted on separate tripods and masts. Soil-heat-flux transducers and averaging soil-temperature thermocouples were installed below the soil surface. Field personnel visited all sites about every 2 weeks during the spring, summer, and early fall and every 4 to 6 weeks in the winter.

Several problems with the instrumentation resulted in incomplete or erroneous data. Burrowing animals damaged the soil-heat-flux transducer wires at the Snively Basin and the Turnbull meadow sites on several occasions. At the Snively Basin site, the motor driving the pump for the cooled-mirror hygrometer ran intermittently between June 25 and July 10, 1990; the pump was replaced July 11, 1990. At the Snively Basin site on August 21, 1990, rain or hail from a thunderstorm broke the lower fine-wire thermocouple; the thermocouple was replaced September 6, 1990. Ice formed on the mirror of the cooled-mirror hygrometer on several occasions at the Snively Basin site during October 1990 and September 1991; at the Turnbull meadow site during July and September 1991.

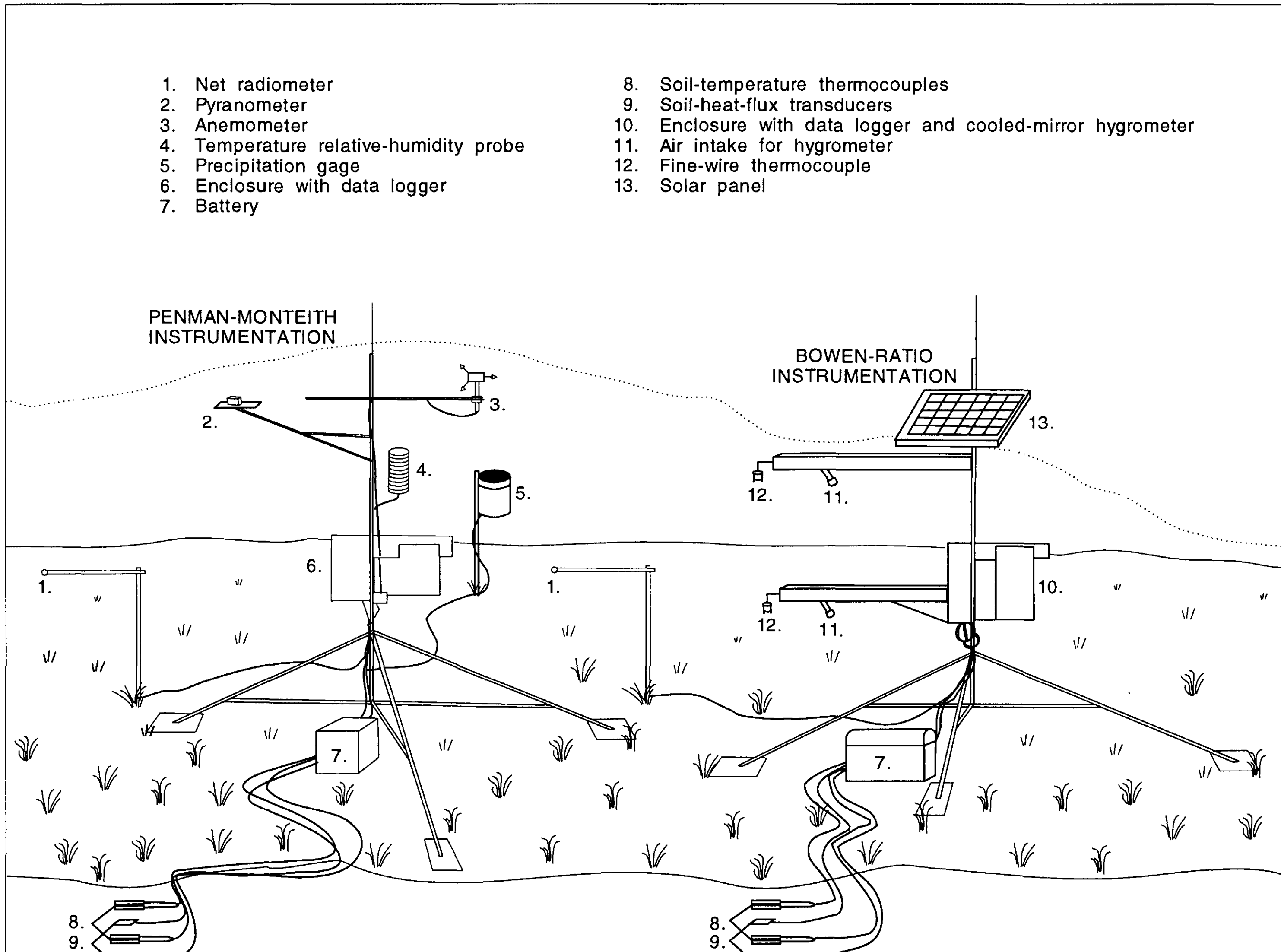

Figure 2.--Instrumentation setup at the evapotranspiration sites.

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

Instrument type	Function	Manufacturer (Model)
Data logger	Scan instruments, record and process data	Campbell Scientific (CR-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)
Precipitation gage	Measure precipitation	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)
Fine-wire thermocouple	Measure air temperature	Campbell Scientific (FWTC-1 and FWTC-3)

Energy-Budget Methods

The equations used in the energy-budget methods for the study are shown on pages vii to x, and the symbols on pages vi and vii. Detailed information on the equations for this specific study are presented by Tomlinson (1994). Additionally, the Bowen-ratio, Penman, 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). These texts may differ from this report in the notation and form of the equations, 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. It can be described as part of an energy budget, which has four main flux components: net radiation, latent-heat flux, sensible-heat flux, and soil-heat flux. These energy fluxes, as they are commonly called, are energy-flux densities ("flux" is used to mean "flux-density" throughout this report) which represent energy flow per unit horizontal surface area. Field measurements of the energy-budget components are made in a horizontal soil-atmosphere boundary layer with an upper canopy just above the plant canopy and a lower boundary just below the soil surface (fig. 3). In the energy-budget equation (eq. 1), net radiation equals the sum of the other three fluxes.

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

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

Sensible-heat flux, H, results from heating of the air just above the soil and vegetative surface. It represents the convective transfer of energy between these surfaces and the atmosphere. In this report, sensible-heat flux is considered positive when heat is transferred upward from the surfaces across the upper boundary of the canopy layer. During the daytime, positive sensible-heat flux is often the result of a surface temperature greater than air temperature. At night, sensible-heat flux is often negative, the result of the surface cooling below the air temperature.

Soil-heat flux, G, represents energy moving downward through the soil from the land surface (eq. 4). Temperature gradients in the soil are measured by soil- heat flux tranducers. The transducers measure the gradient across a material of known thermal conductivity. Although the thermal conductivity of the soil changes with soil-moisture content and probably differs from the tranducer material conductivity, 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.

The Bowen-ratio, Penman, and Penman-Monteith methods all incorporate energy-budget principles. The Bowen-ratio method is strictly an energy-budget method. The Penman and Penman-Monteith methods use turbulent-transfer theory as well as energy-budget principles, and therefore are more accurately termed combination methods. They are discussed here, however, because their main focus is still energy-budget theory.

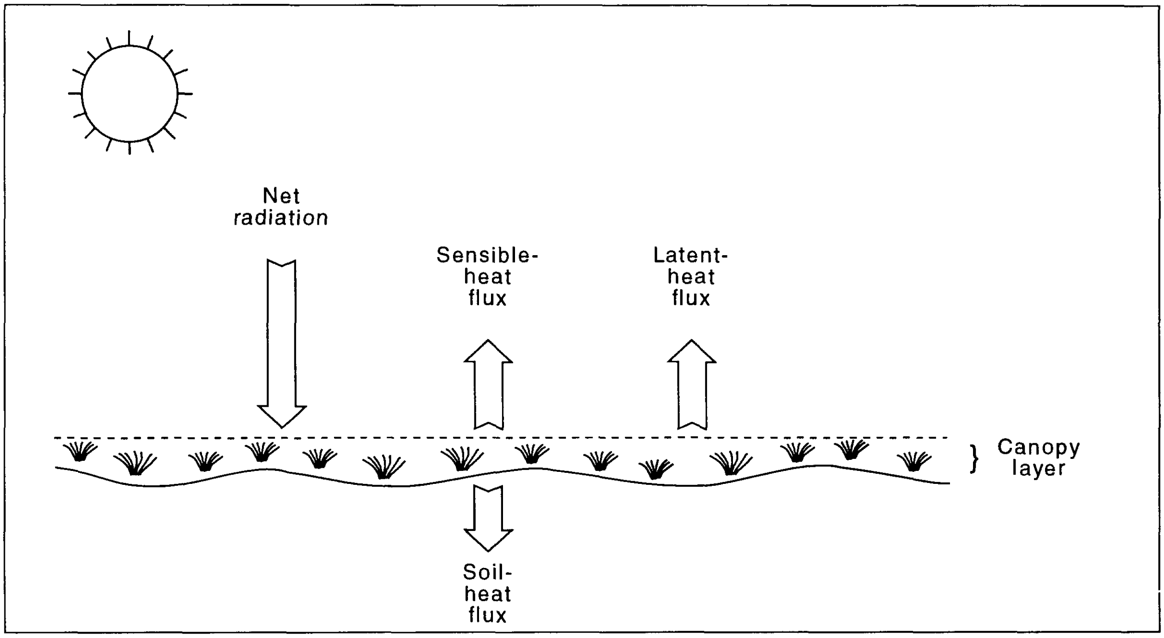

Figure 3.--Schematic of energy budget for Snively Basin site.

Bowen-Ratio Method

The ratio of sensible-heat flux is now 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 over a surface (eq. 7) under certain conditions. The gradients can be 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. When there is no net horizontal advection, the coefficients (eddy diffusivities) for heat and water vapor transport, K_h and K_w, respectively, are assumed to be equal. With this assumption (eq. 8), and the reduction 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 can be solved for the sensible-heat flux (eq. 11) and latent-heat flux (eq. 12). The rate of ET can then be determined using the latent-heat flux, latent-heat of vaporization of water, and a factor (86.4) that accounts for conversion of units (eq. 13a).

Penman and Penman-Monteith Methods

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

Penman (1948) was the first to introduce an equation for evaporation from open water (Brutsaert, 1982, p. 215). Later, Penman (1956) described an equation to determine potential ET over any wet surface, which assumed that the resistances to diffusion of atmospheric heat and of vapor were equal. This equation (eq. 18) has been refined over the years and can estimate potential ET accurately under conditions of unlimited water supply, such as 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 water is limited.

By accounting for the resistance due to plant stomatal closure, plant senescence, and partially dry soil, variations of the Penman equation enable more realistic estimation of actual ET when water is in limited supply. One variation developed by Monteith (1963b), termed the Penman-Monteith equation (eq. 19), adds a bulk canopy resistance term (eq. 20) to the basic Penman equation. This resistance is a combination of the resistances to evaporation due to dry soil and to transpiration due to stomatal closure or senescence. Canopy resistance is not easily measured, however. In practice, the canopy resistance is not measured directly, but is 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. This was the approach used in this study.

Weighing Lysimeters

Weighing lysimeters provide the most direct method for estimating evapotranspiration (Kirkham and others, 1991). When the lysimeter soil profile and vegetation types and density properly represent the surrounding area, lysimeters are considered the standard by which other methods, such as Bowen-ratio and Penman-Monteith, are evaluated. In their simplest design, lysimeters are containers of soil buried in the ground, flush with the soil surface. The containers are weighed periodically to measure moisture changes. In some cases, the entire container is removed from the ground for weighing.

Monolith weighing lysimeters employ a box-within-a-box construction. The inner box contains a monolith of soil and vegetation that is as undisturbed as possible. The inner box rests on a scale for measurements of mass. The outer box acts as a retaining wall for the soil profile surrounding the lysimeter. Changes in mass result from evapotranspiration and precipitation. Monolith weighing lysimeters installed and maintained on the ALE Reserve by Battelle, Pacific Northwest Laboratory use platform-type scales that are accurate to 50 grams, equivalent to 0.02 millimeters of water (Gee and others, 1991). The surface dimensions of the inner boxes of the ALE Reserve lysimeters are about 1.5 meters square and range from 1.4 meters to 1.6 meters deep (Kirkham and others, 1991).

The scales at the grass lysimeter site produce voltages that are measured every 10 seconds and averaged every hour (Gee and others, 1991). The hourly average voltages are converted to mass in kilograms by adding 1 to the voltage and multiplying the result by a calibration factor (R. Kirkham, Battelle, Pacific Northwest Laboratories, written commun., 1991). For lysimeter 1, the factor is 4650.2527 kilograms per volt; the factor for lysimeter 2 is 4646.3382 kilograms per volt. The difference between the weights can then be converted to ET in millimeters per day as follows: divide the weight difference, in kilograms per hour, by 23,104 square centimeters (the area of each lysimeter); multiply the result by 10,000 millimeters per kilogram per square centimeter to obtain millimeters per hour; subtract precipitation for the hour, in millimeters per hour, from the result; multiply by 24 hours per day to obtain ET in millimeters per day. To obtain daily estimates of ET, sum the 24 hourly rates together and divide the total by 24. An alternate method to obtain daily estimates is to use the above procedure with midnight-to-midnight voltage values.

DATA AND ERROR ANALYSES

In this study, energy-budget fluxes and ET were calculated with a combination of the Bowen-ratio and Penman-Monteith methods. These methods incorporate a number of parameters; some of them can be highly interpretive, such as the aerodynamic resistance to heat and the canopy resistance. The accuracy of these parameters affects the flux and ET calculations made with the Bowen-ratio and Penman-Monteith methods. The primary sources of error are instrumentation, the aerodynamic resistance estimates, and canopy resistance estimates. These errors were small except for periods when the latent-heat flux was near zero.

Instrumentation

To check the precision of the instruments in the field, two sets of Bowen-ratio instrumentation were compared with one set of Penman-Monteith instrumentation at the Snively Basin site from September 5-13, 1991. The sets were located about 1.5 meters from one another.

Net radiation, air temperature, relative humidity, and vapor pressure agreed within 10 percent of one another. The soil-heat-flux transducer measurements were more variable and agreed within 30 percent. For all instruments, only daytime values ($R_n > 0$) were compared. Nighttime values from some instruments, especially the net radiometers and soil-heat-flux transducers, did not always agree. During the night, ET is usually near zero, however, so variabilities among the instruments at night have negligible effect on the daily ET estimates.

In the test from September 5-13, 1991, three net radiometers were set up and data from them were compared (fig. 4). Two of these had been in the field for about 6 months; one net radiometer was newer and only recently installed. During the daytime, these net radiometers agreed within 4 percent of their mean value. Net radiation was the least variable of the parameters that were checked and was also one of the most important in the calculations. In the Bowen-ratio method, for example, a 4-percent change in the net radiation value also changes the ET estimate by about 4 percent.

Data from five soil-heat-flux transducers were compared (fig. 5). Two of these had been installed for about 15 months. One had been installed for about 6 months. The other two were newer and only recently installed. During the daytime, the transducers agreed within 28 percent of their mean. Although this may seem like a significant lack of precision, changing the soil-heat flux, including the portion represented by soil-heat storage, by 28 percent only changes the ET estimate by 0.5 percent. Therefore, the variabilities of these transducers were not a major concern in the calculation of ET at the grass-covered Snively Basin site.

Air temperature measured by two fine-wire thermocouples and one Campbell-Scientific CR-207 probe at 2.0 meters above the canopy also were compared. When differences were averaged over the 9-day period, all instruments agreed within 4 percent of their average value (fig. 6). It was expected that the fine-wire thermocouples would agree more closely; however, this was not the case. On some days, the fine-wire thermocouples agreed only within 10 percent. Each sensor was connected to a different data logger and each data logger can impart some variability, perhaps due to minor corrosion on internal connections (J. Greene, Campbell Scientific, Inc., oral commun., 1992) or to differences in thermocouple reference temperatures (W.D. Nichols, U.S. Geological Survey, written commun., 1993). Thus, some differences in variability in the air temperatures might be expected. Also, though the fetch (extent of similar vegetation and topography) at the site visually appeared uniform (which the uniformity of the net-radiometer readings appeared to substantiate), the surface may have heated unevenly and had an effect on the air temperature.

Small variability in air temperature is not a major concern in the calculation of ET with the Bowen-ratio method, however, because a consistent 4-percent change in air temperature at both measurement heights does not change the ET calculation. In the Bowen-ratio method, the air temperature difference, or gradient, between two heights is important; changing the air temperature difference by 4 percent would change the ET estimate by almost 4 percent. In the Penman-Monteith method, on the other hand, a 4-percent change in the air temperature produces a 4-percent change in calculated ET. Changes were obtained by using dummy values for the air temperature (or air temperature difference) for several 20-minute daytime periods from September 5-13, 1991, in the Bowen-ratio and Penman-Monteith equations, solving for ET, and comparing those ET values with the ones obtained for the same time periods using the original (unmodified) air-temperature data. Large amounts of spider webbing contaminated the upper thermocouple of one of the Bowen-ratio systems, precluding an accurate assessment of the air-temperature gradient differences between the Bowen-ratio systems.

Vapor pressure and relative humidity measured by two DEW-10 chilled-mirror hygrometers and the CR-207 probe at 2 meters above the canopy were compared. The vapor pressures and relative humidities calculated with data from these instruments are shown on figure 7. On the average, for periods with accurate vapor-pressure data (September 6, 7 and parts of September 5, 8, and 11), the vapor-pressure values agreed within 8 percent and relative humidities agreed within 10 percent. Periods that were not used were those when ice had formed on the DEW-10 cooled mirror; periods of ice (labeled on figure 7) show as sharp departures below the average of the other measurements. Because ice formation on the cooled-mirror of one of the DEW-10 instruments was so extensive, assessment of the vapor-pressure gradient between the Bowen-ratio systems could not be made for the entire period of September 5-13. For the non-ice periods from September 5-7, the vapor-pressure gradients between the two systems varied 10 percent.

In summary, the differences between like instruments produced little error in the resultant ET calculations. In a worst-case scenario, if all the instruments had varied by the maximum amount, only a 12-percent change would occur in the final ET calculated with the Bowen-ratio method. Because the instruments could not be set up at exactly the same location, some of the measured differences during the tests probably cannot be completely attributed to the instruments themselves. Rather, variabilities in air temperature and relative humidity, soil, wind, and vegetation likely produce some of the variability.

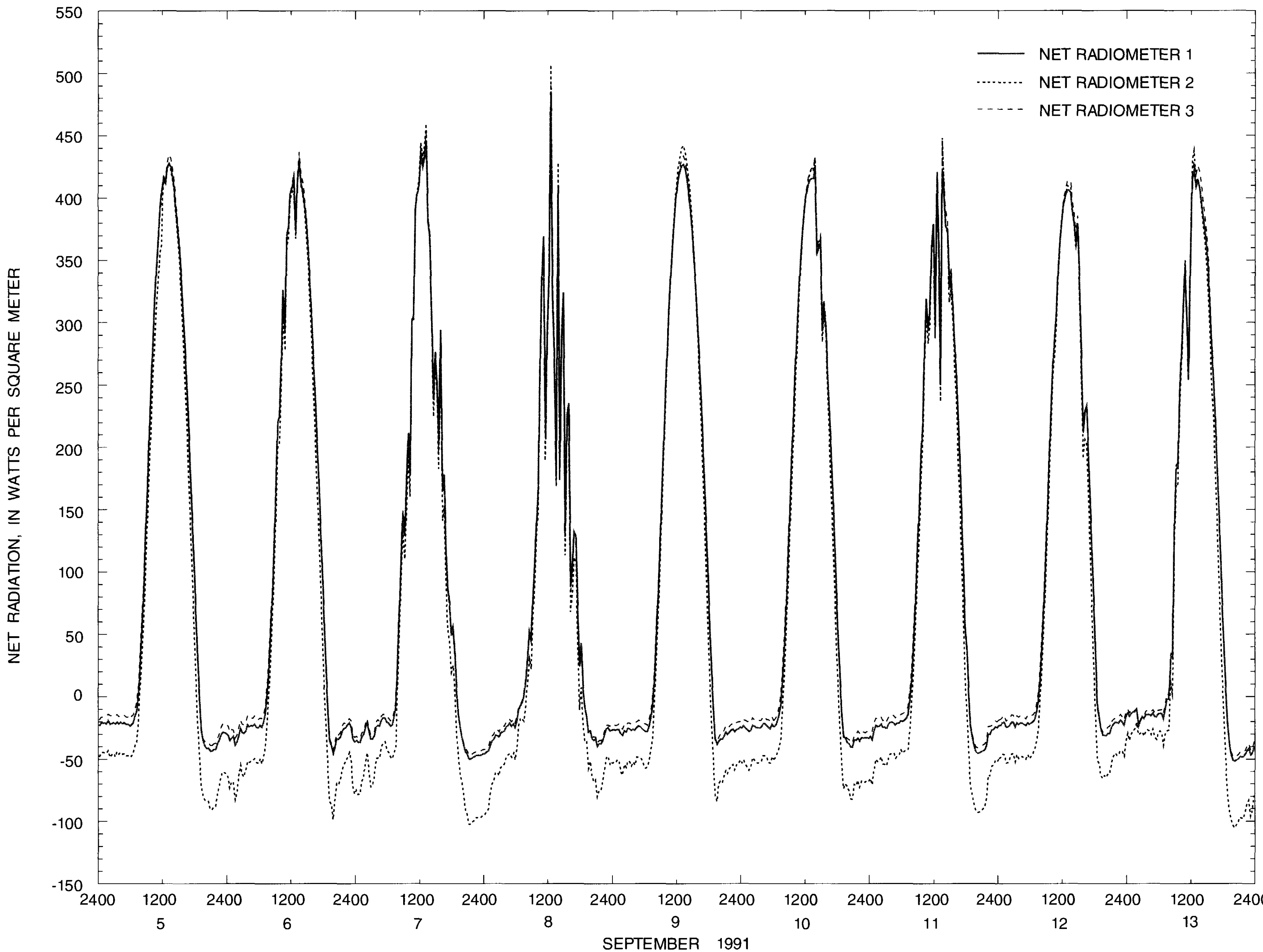

Figure 4.--Net radiation at the Snively Basin site, September 5-13, 1991.

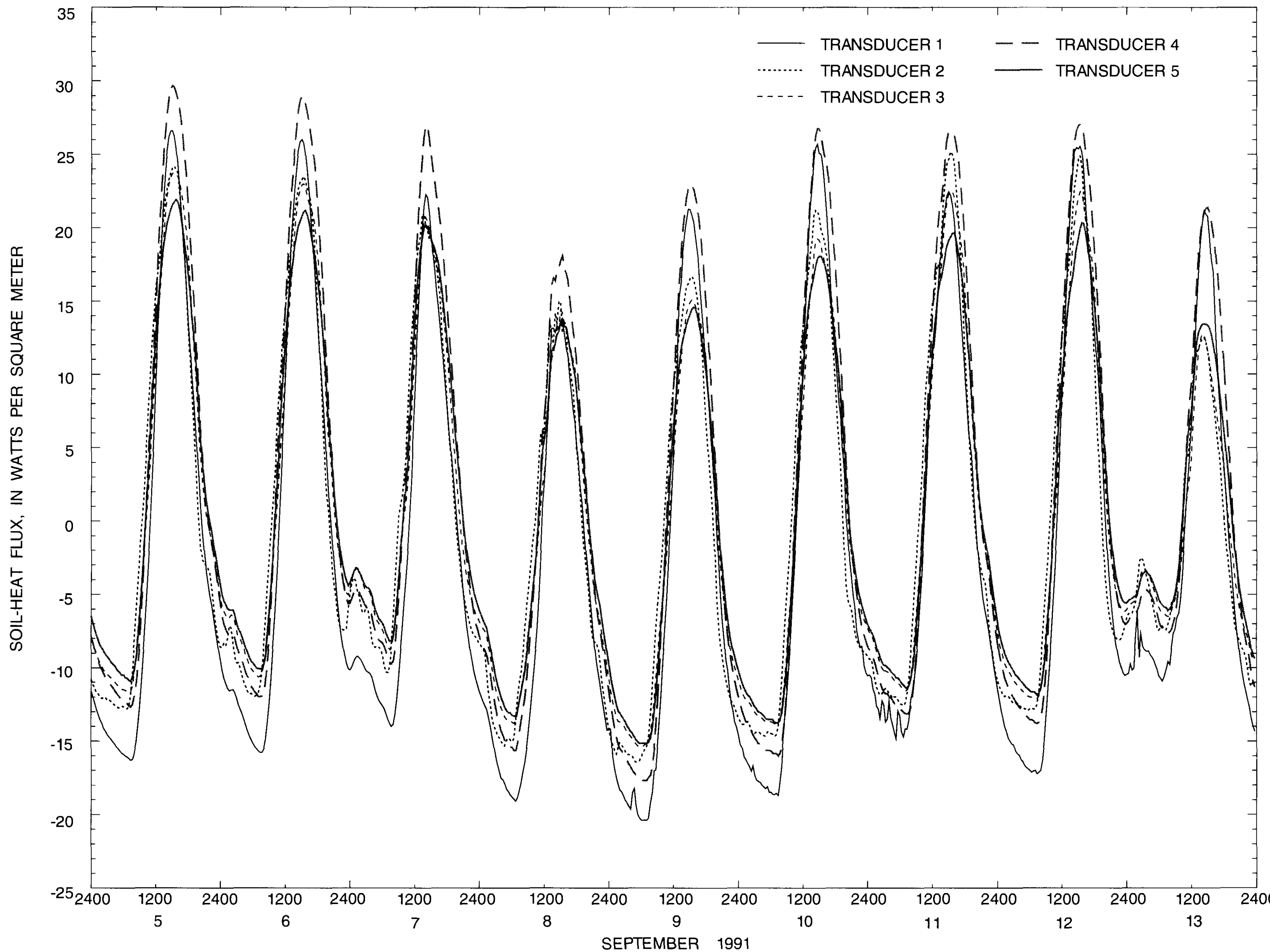

Figure 5.--Soil-heat flux at the Snively Basin site, September 5-13, 1991.

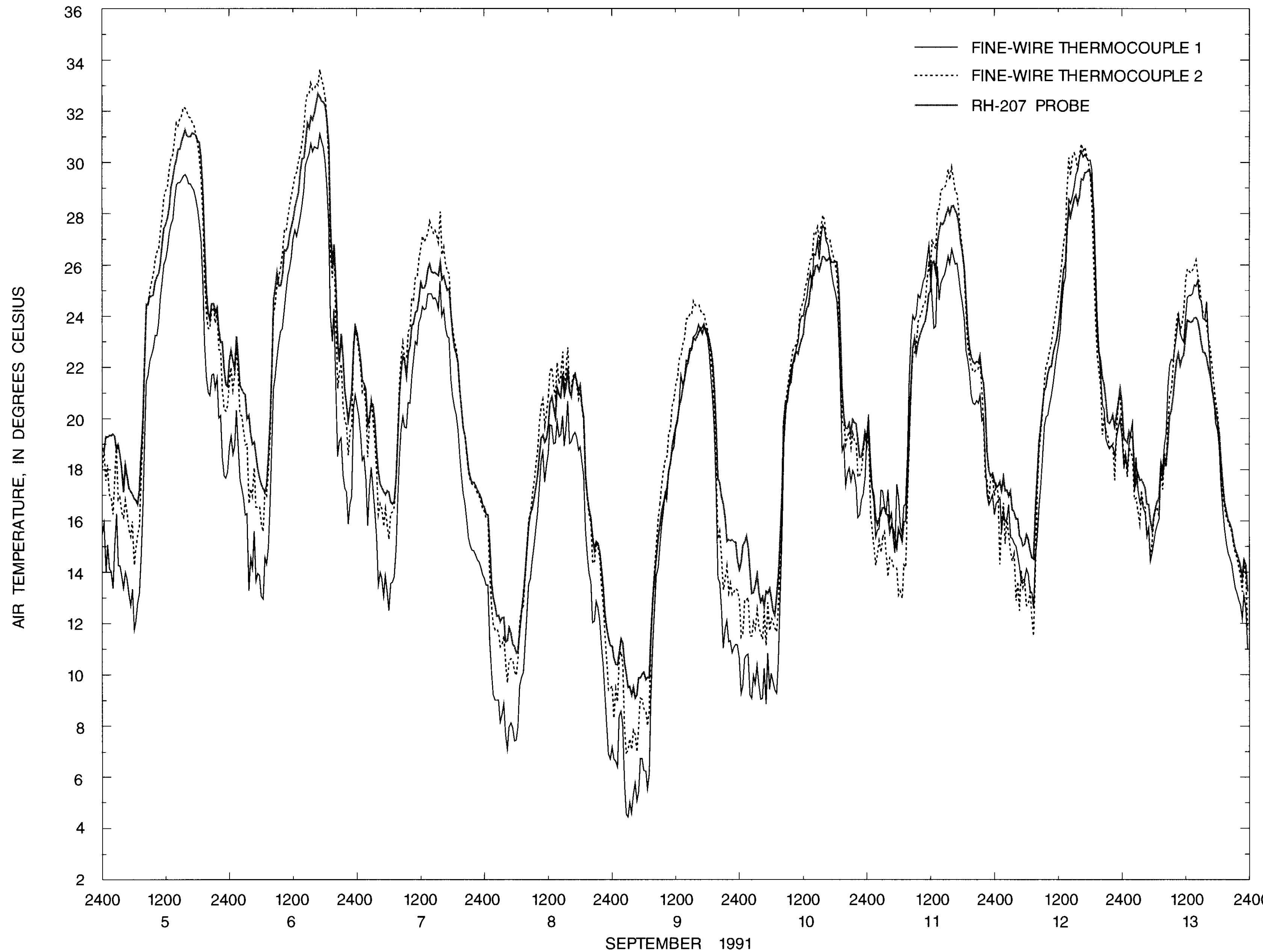

Figure 6.--Air temperature at the Snively Basin site, September 5-13, 1991.

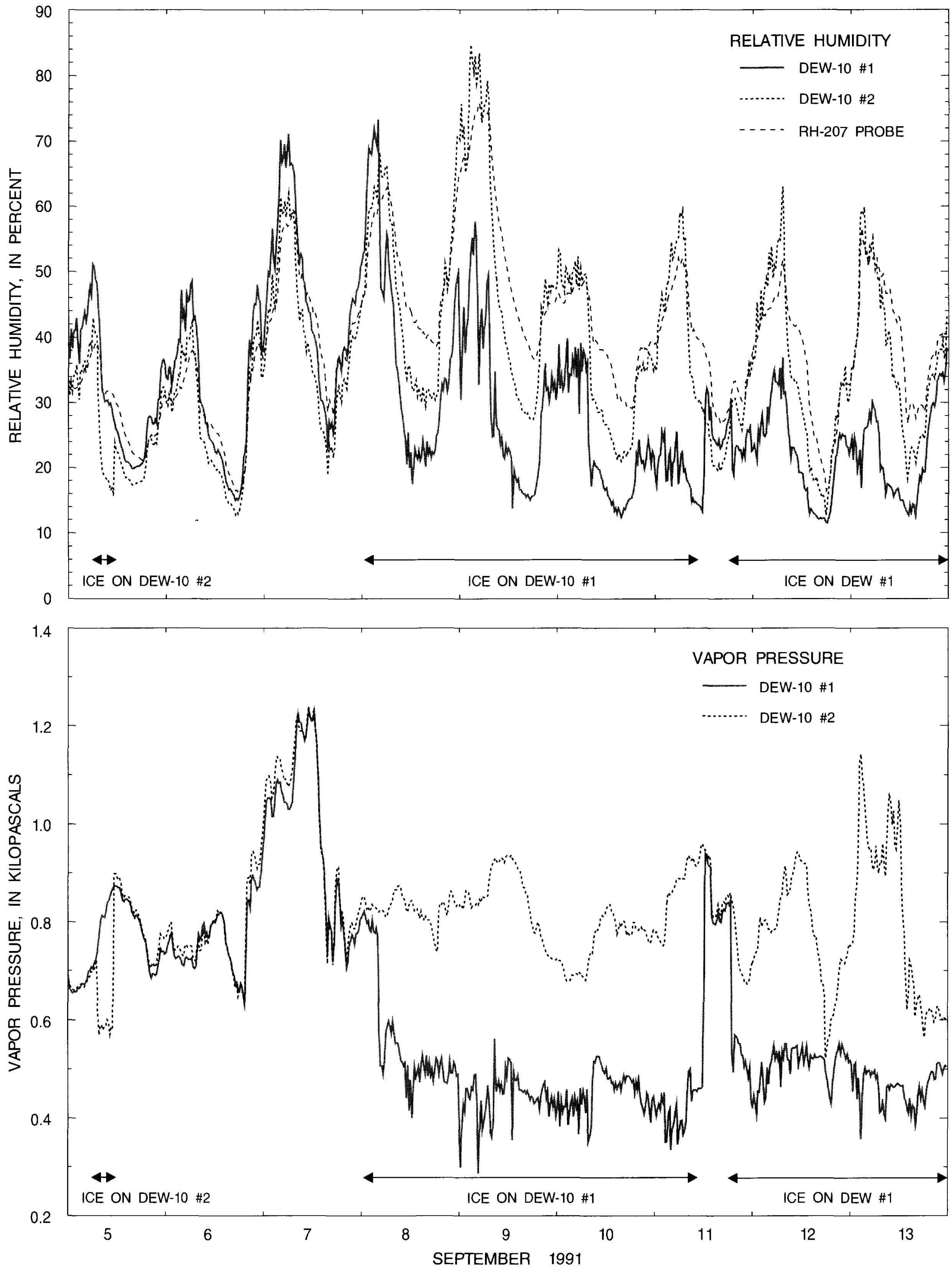

Figure 7.--Relative humidity and vapor pressure at the Snively Basin site, September 5-13, 1991.

Aerodynamic Resistance to Heat

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 the values of aerodynamic resistance to heat needed in the Penman and Penman-Monteith methods. These methods commonly use wind-speed (turbulence) theory and can produce different estimates of the resistance. Wind-speed theory is complex and some of the accurate measurements needed are often difficult to obtain. Some methods apply only to neutral periods (sensible-heat flux, H, = 0), others only to stable periods ($H < 0$) or unstable periods ($H > 0$). The primary goal in this study was to use a method that was simple to apply and produced reasonable estimates of ET when used in the Penman-Monteith method compared with ET estimates obtained using 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 applies only during neutral conditions. For unstable conditions, a profile-stability correction for sensible heat, Ψ_h, should be added to the equation. However, solving for the profile-stability correction involves a series of extremely complex iterative calculations. Although 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 not used the stability correction in their calculations for wildland ET and have produced reasonable results (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).

To test whether an incorrect r_h value would have much effect on the calculations of ET, r_h was overestimated by a factor of two for 15 daytime periods in April, June, and July 1991 at the Snively Basin site. The periods chosen were definitely unstable: winds were fairly low, between 1 and 5 meters per second; net radiation and sensible heat were comparatively high, greater than 200 watts per square meter; and soil-heat flux was also high, greater than 20 watts per square meter.

Estimating r_h through equation 17 and doubling it in the Penman-Monteith equation lowered the estimated canopy resistance by 30 percent and the ET estimate by 3.5 percent, the latter value within the range of the precision errors introduced by the instruments. Furthermore, the data show that the canopy resistance frequently varied by 30 percent, or more, even during neutral conditions. Using the stability-correction factor in this study would not result in more accurate daily estimates of ET; therefore, it was not used. The error in r_c is likely to be much less than 30 percent most of the time, because neutral conditions are often approximated with high wind speeds (Stannard, written commun., 1990), which are common at the study sites. Hourly average wind speeds frequently exceeded 5 meters per second, often exceeded 10 meters per second, and occasionally exceeded 15 meters per second.

The terms d, z_m, and z_h on the right-hand side of 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, in meters, z_h, is related to the surface temperature. 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 dense canopies, Campbell (1977, p. 38) suggests that d equals 0.64 times the canopy height, h. For the Snively Basin site, the 0.35 meter-high canopy is somewhat less than dense. Therefore, a value for d lower than 0.64 h seems reasonable because the level of heat, vapor, or momentum exchange will be closer to the surface than for a truly dense canopy. Thus, 0.50 h was chosen, giving a d of 0.18 meter. The value chosen for d does not have major effect on the resulting value for r_h in equation 17 because d is much smaller than the z of 3.0 meters. A value of $d = 0$ changes the overall r_h less than 2 percent from r_h obtained with $d = 0.18$, other values being equal.

For the Snively Basin site, wind-speed data were obtained for a 2-week period at 1, 2, 3, and 4 meters above the canopy, and several wind-speed profiles were plotted to estimate z_m graphically (Tomlinson, 1994). From these profiles, the average value of z_m was 0.004 meter. This value seems reasonable compared with tabular z_m values for full-cover grasses of 0.001 meter to 0.0065 meter (Brutsaert, 1982, p. 114). Based on empirical measurements, Campbell (1977, p. 39) relates that z_h equals

0.2 z_m, or 0.0008 meter for this study. Wind speed was collected at height z, 3.0 meters above the canopy. Substituting the above values for the variables z, d, z_h, z_m, and k into equation 17 and reducing yields

$$r_h = \frac{335}{u} \ .$$

For periods where snow covered the vegetation, d was estimated to be zero (flat surface), z_m was 0.001 meter (Stull, 1988, p. 380), and z_h was 0.0002 meter. Using these values in equation 17 produces

$$r_h = \frac{768}{u} \ .$$

For the sites at the Turnbull NWR, the vegetative canopy is dense and estimates of the aerodynamic resistance to heat can be based on the height of the vegetation. Thus, Campbell's (1977, p.38) estimate of $d = 0.64 \ h$ was used. For dense canopies, Campbell (1977, p. 39) estimates the momentum roughness length, z_m, equals $0.13 \ h$, and the heat-transfer roughness length, z_h, equals $0.2 \ z_m$.

For the Turnbull meadow site, canopy height, h, equals 0.91 meter, so $d = 0.58$ meter, $z_m = 0.12$ meter, and $z_h = 0.024$ meter. Wind speed, u, was collected at height $z = 3.0$ meters. These values in equation 17 give the aerodynamic resistance to heat as

$$r_h = \frac{88.5}{u} \ ,$$

with terms as defined previously. For the Turnbull marsh site, $h = 0.61$ meter, so $d = 0.39$ meter, $z_m = 0.079$ meter, and $z_h = 0.016$ meter. Using these values with a $z = 3.0$ meters in equation 17 gives

$$r_h = \frac{113}{u} \ .$$

Snow did not fall during the spring, summer, and early fall data-collection periods for the Turnbull NWR sites; therefore, no adjustments were made for snow conditions.

Estimates of d, z_m, z_h, and r_h were not made for the grass lysimeter site because the Penman-Monteith method was not used to estimate ET for that site.

Canopy Resistance

Canopy resistance is the resistance to water and vapor transport resulting from partially dry soil and plant leaf stomatal closure. The canopy resistance represents a bulk value including both soil and plant terms, and one term may exhibit a greater effect than the other on the whole resistance value, depending on site conditions. At the Snively Basin site, for instance, in late summer when the grasses have gone dormant or have perished, the canopy resistance probably represents only the soil's resistance to vapor transport. The canopy resistance is a function of net radiation, air temperature, relative humidity, stage of plant growth, season of the year, aerodynamic resistance to heat, and soil moisture.

Regression analysis comparing soil moisture and canopy resistance required logarithmic transformation to linearize the data at the Snively Basin and Turnbull meadow sites (fig. 8). For the Snively Basin site data, the best-fit curve through the transformed data produced an r^2 (square of the correlation coefficient) of 0.63. For the Turnbull meadow site data, the results were better; the best-fit curve through the transformed data produced an r^2 of 0.82.

The canopy-resistance estimates used with the Penman-Monteith method were daily averages of canopy resistance calculated from equation 20 with latent-heat fluxes from the Bowen-ratio method for each time interval. The time interval was 20 minutes for Bowen-ratio and Penman-Monteith data except for data from May 30 to July 31, 1990, from the Snively Basin site, for which hourly averages of latent-heat flux were calculated to correspond with the hourly Penman-Monteith data. Canopy resistances were calculated for daytime periods from about 8 a.m. to 5 p.m., when ET was highest.

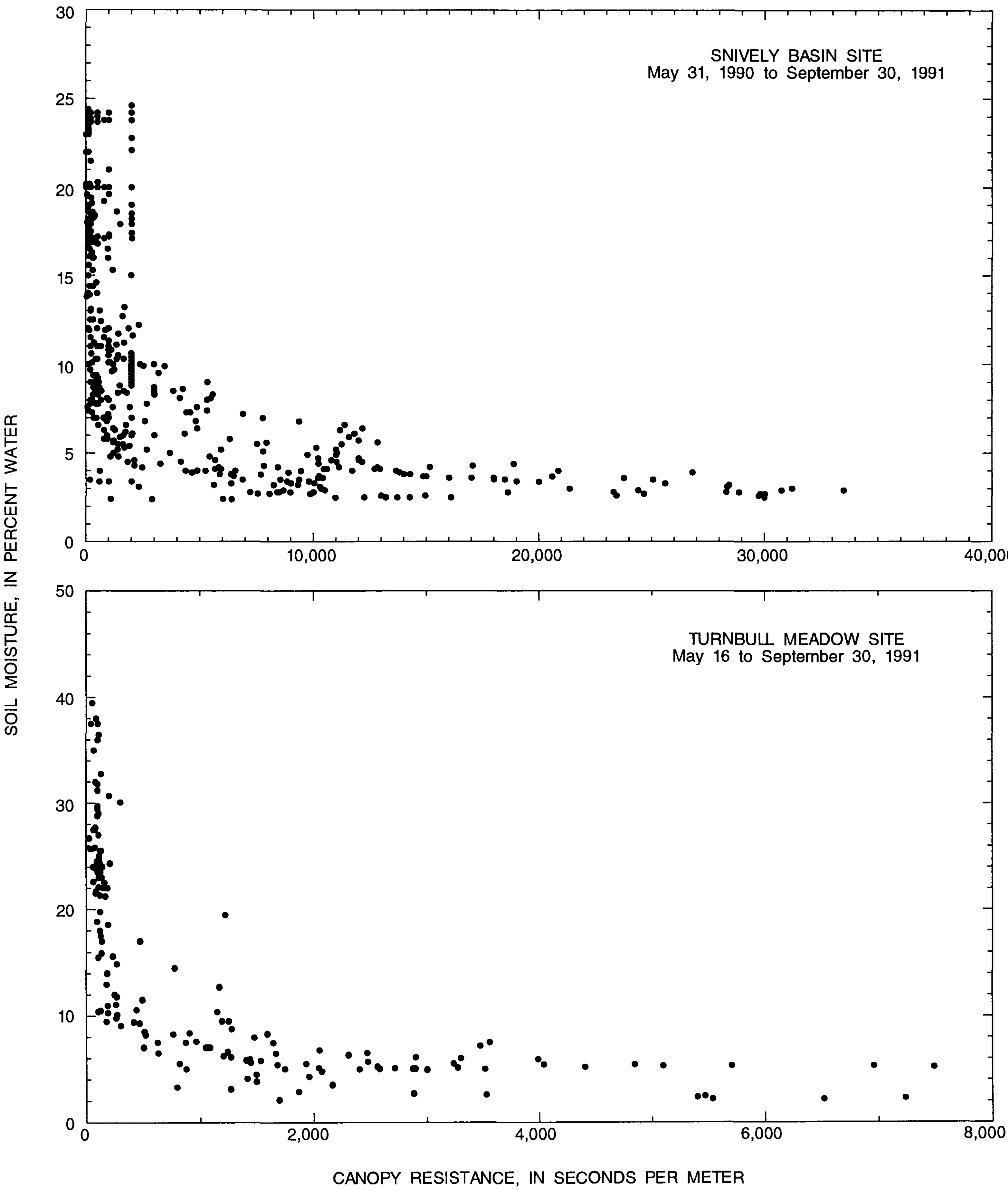

Figure 8.--Soil moisture and canopy resistance at Snively Basin site from May 31, 1990 to September 30, 1991, and Turnbull meadow site from May 16 to September 30, 1991.

Vapor-pressure and air-temperature differences data needed to calculate latent-heat fluxes with the Bowen-ratio method were incomplete because of sensor problems or adverse environmental conditions. The latent-heat fluxes that were calculated with the intermittent Bowen-ratio data were used to find the canopy resistance in Penman-Monteith equation. This produced a set of canopy resistances for a number of periods for each day. These canopy resistances were averaged for each day. Then, the latent-heat flux was recalculated for every time interval with the Penman-Monteith method and the daily average canopy resistance. For days with no Bowen-ratio latent-heat fluxes, canopy resistances were interpolated from resistances estimated on adjacent days. Because data needed to compute ET with the Penman-Monteith method were complete for all time intervals in the period of study, the approach described in this paragraph allowed ET to be calculated for every day of the study period.

The method of averaging the calculated canopy resistances from each 20-minute or hourly interval probably produced some error in estimation of latent-heat fluxes and ET because the canopy resistances often varied by more than 100 percent from one interval to another. Latent-heat fluxes calculated with the Bowen-ratio and Penman-Monteith methods were compared for three 6-day periods that represent most of the conditions seen over the period of study at the Snively Basin site (fig 9) and the Turnbull meadow site (fig. 10). Because the canopy resistance served as a calibration factor between the two methods, the difference between these latent-heat fluxes is due directly to the difference between the actual canopy resistance for each time interval and the daily average canopy resistance. On most days, the difference was small. On some days, however, discrepancies were large due to several factors: rain followed by fast drying of the soil surface, stomatal closure as the day became warmer and drier, instrument error, or erroneous data collected during periods of possible advection of moisture or sensible-heat. On days without precipitation, such as March 21-23, 1991, and April 11-13, 1991 (fig. 9) and May 20-22, 1991, and June 8-10, 1991 (fig. 10), the close agreement between the actual and average canopy resistances provided good agreement between Bowen-ratio and Penman-Monteith calculated latent-heat fluxes.

On days with or shortly after heavy precipitation, March 24-26, 1991 (fig. 9) and May 18, 1991 (fig. 10), for example, the Bowen-ratio latent-heat flux sometimes exceeded the Penman-Monteith latent-heat flux. The Bowen-ratio calculated latent-heat flux sometimes slightly exceeded the net radiation. The source for this extra latent-heat flux may be either soil-heat flux, wherein energy from the soil was used to heat or evaporate rain water, or advected sensible-heat flux, wherein warmer, drier air from adjacent areas provided additional energy for evaporation. When the Penman-Monteith equation was adjusted for the canopy resistance with the Bowen-ratio latent-heat fluxes, negative canopy resistances resulted. Also, rainwater on top of the net radiometer may have affected the instrument readings and contributed to the negative resistances (R.R. Kirkham, oral commun., 1993). Because resistances cannot be negative, zero values for these periods were used for the canopy resistance in the Penman-Monteith equation. The net result for March 24, 1991 (fig. 9) was a 35-percent underestimation of latent-heat flux and ET by the Penman-Monteith method. However, this was one of the worst-case examples for the period of study. During other rainy days, such as June 21, 1991 (fig. 9) or June 29, 1991 (fig. 10), differences in latent-heat fluxes calculated with the two methods averaged less than 10 percent from one another.

On some days, June 16 and 18, 1991 (fig. 9) and July 1-2, 1991 (fig. 10) for example, canopy resistances varied by as much as 100 percent during the course of the day as drying and stomatal closure occurred, and latent heat fluxes calculated with the two methods did not agree well. However, on a daily basis, these differences averaged out, as the closeness of the Bowen-ratio and Penman-Monteith estimates of ET show (see tables 2 and 4).

During the growing season, when latent-heat flux calculations were considered inaccurate or could not be calculated because of missing data for an entire day or more, canopy resistances were interpolated from canopy resistances calculated on adjacent days. For the Snively Basin site, canopy resistances for some days with missing Bowen-ratio data were estimated from latent-heat fluxes calculated from weighing-lysimeter data at the grass lysimeter site. Fortunately, most of the estimated periods occurred when ET was near zero, so the cumulative effect of estimation errors on monthly, seasonal, or annual ET was small. For instance, doubling the estimated ET for the Snively Basin site for all of August and September 1991 increased the ET for the period June to September 1991 only by 11 percent, and for the period October 1990 to September 1991 the ET increase was only by 3 percent.

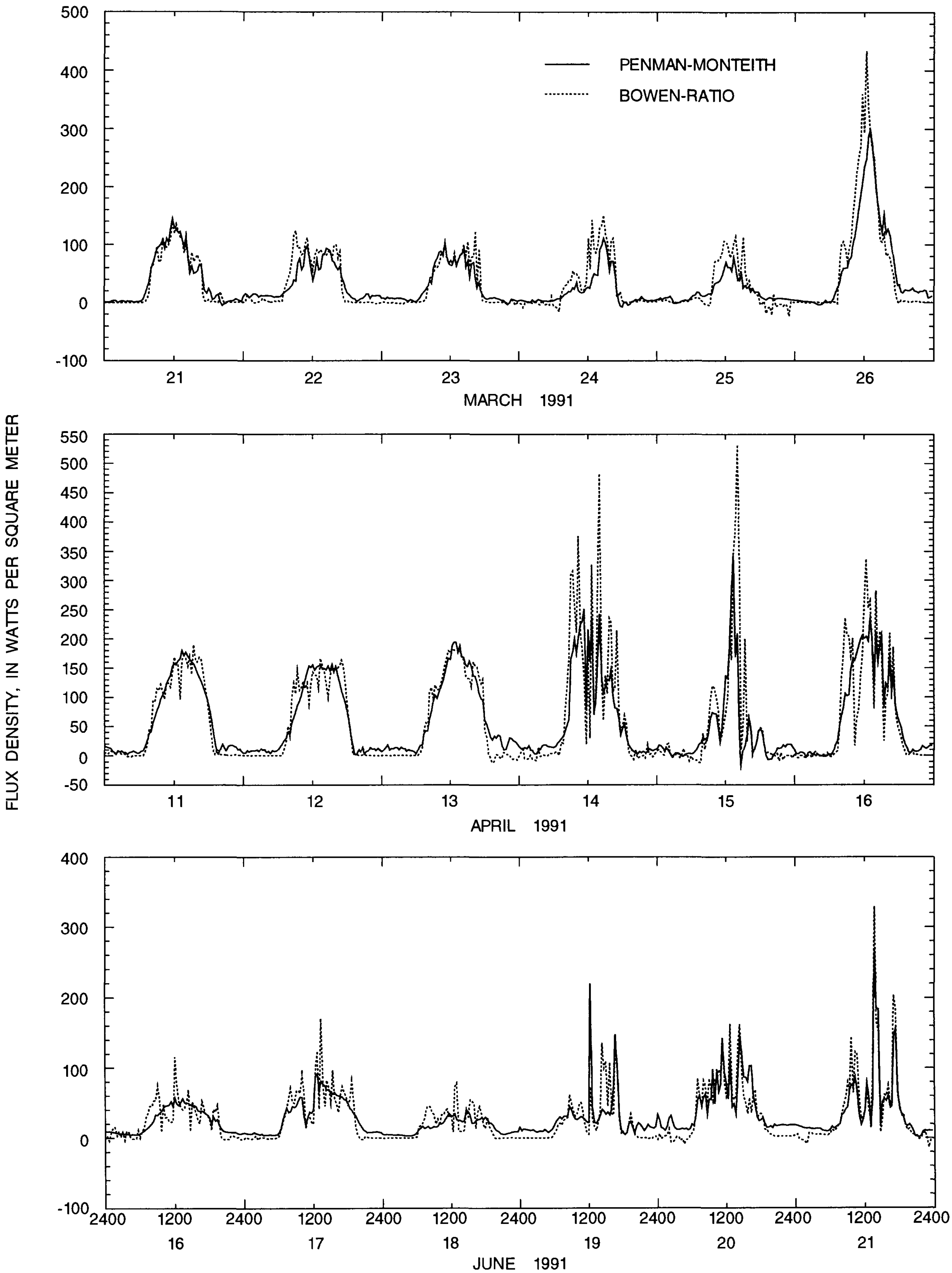

Figure 9.--Latent-heat flux calculated with the Bowen-ratio and Penman-Monteith methods at the Snively Basin site for selected periods from March 1991 to June 1991.

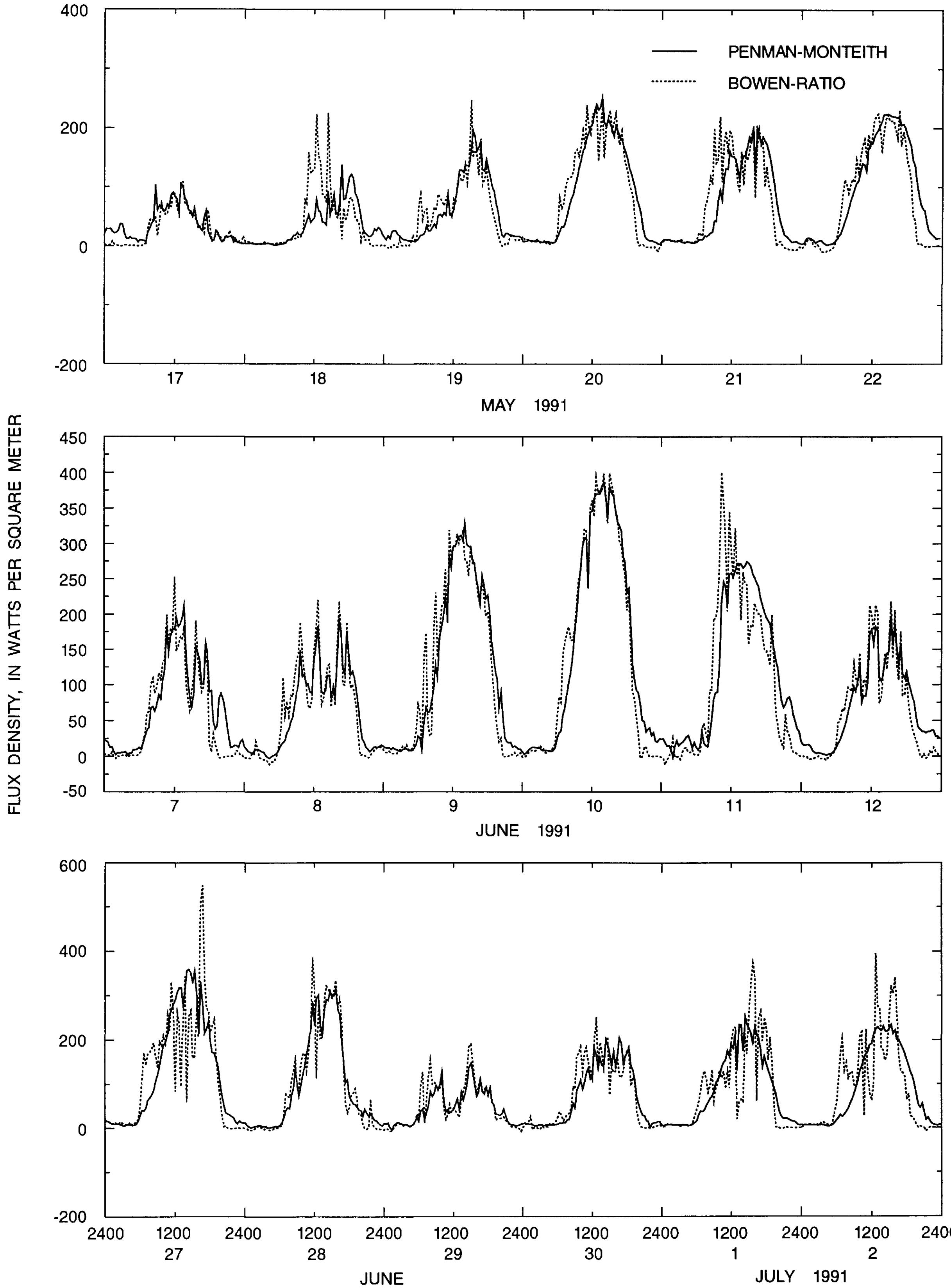

Figure10.--Latent-heat flux calculated with the Bowen-ratio and Penman-Monteith methods at Turnbull meadow site for selected periods from May to July 1991.

During the late fall and winter at the Snively Basin site, when no Bowen-ratio data were available, daily canopy resistances for the Penman-Monteith method were estimated. During periods of rain or snow, 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 with latent-heat fluxes calculated by the Bowen-ratio method were usually near zero. Daily canopy resistances were increased each subsequent day after the precipitation, up to a maximum of 3,000 seconds per meter, to reflect the drying of the soil surface. This seemed a reasonable maximum canopy resistance for a dry soil surface at this time of year compared with canopy resistances calculated in late June and early July, when plants were approaching dormancy and surface soil moisture was not entirely depleted; these are conditions similar to those in fall and winter (although the source of plant stress is the cold rather than the heat). Estimates of canopy resistance were often highly subjective during the fall and winter, because the speed at which the soil surface dried after rainfall or snowmelt could only be estimated. At other times, estimating the canopy resistance was simplified because of rainfall or snow cover (zero canopy resistance). Irrespective of canopy resistance, little ET could have occurred from November through February because net radiation was so low (often less than 100 watts per square meter). Therefore, although the daily errors in estimating the canopy resistance may occasionally be high (as much as 100 percent or more), the effect on monthly or seasonal ET is probably small. This is supported by the close balance between precipitation and ET in the water budget for the Snively Basin site.

The agreement of the Penman-Monteith calculations with the Bowen-ratio calculations for days with changing environmental 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 one used in the time intervals when it was not ($r_c > 0$). The changes in r_c 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 daily-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.

Estimates of canopy resistance may include errors from calculation of other variables, such as the aerodynamic resistance to heat, r_h. As discussed in the previous section, the equation used in this study to estimate r_h can sometimes overestimate that term during periods of unstable atmospheric conditions. An overestimation of r_h by a factor of 2 results in an overestimation of r_c by about 30 percent. However, the effect is not significant because only a 3.5-percent change in ET results.

During many days in summer and fall at the Snively Basin site, latent-heat fluxes calculated with the Bowen-ratio method often appeared erroneous—they were large-magnitude positive or negative numbers. This was due to noise (irregular back-and-forth pattern of values) in the vapor-pressure data and reversals in the vapor-pressure gradient. On days when there was noise in the vapor-pressure gradient data, latent-heat fluxes calculated with the Bowen-ratio method for periods believed to have data representative of site conditions were used to determine the daily average canopy resistance in the Penman-Monteith method; other periods were not used. For example, on some days there were noisy vapor-pressure data possibly due to ice on the DEW-10 mirror in the morning. This ice melted around noon and vapor-pressure data appeared to be accurate in the afternoon. Thus, only the afternoon data were used to determine the canopy resistance for the whole day. In other cases, the noise in vapor-pressure data may have been due to instrument anomalies or dry environmental conditions.

In summary, the canopy resistance, r_c, was used as an overall calibration factor between the Bowen-ratio and Penman-Monteith methods of estimating ET. The resistances incorporate errors from a variety of sources. These errors appear to average out for the most part, however, and generally good agreement between Bowen-ratio and Penman-Monteith latent-heat fluxes result.

RESULTS

Energy budget fluxes, ET estimates, environmental influences, and water budgets provided a variety of information needed to evaluate ET at the Snively Basin, grass lysimeter, and Turnbull meadow and marsh sites. The Bowen-ratio method estimated about 41 percent of the ET measured by weighing lysimeters at the grass lysimeter site in April and May 1991. For the Snively Basin and Turnbull meadow sites, Penman-Monteith ET differed less than 35 percent from Bowen-ratio ET. ET at the Turnbull marsh site averaged 65 percent higher than ET at the Turnbull meadow site. A water budget for the Snively Basin site indicated that all precipitation received between August 20, 1990, and September 30, 1991, returned to the atmosphere as ET.

Energy-Budget Fluxes

In an energy budget, net radiation equals the sum of soil-heat flux, sensible-heat flux, and latent-heat flux (eq. 1). Previous sections have discussed the measurement and determination of these fluxes with the Bowen-ratio and Penman-Monteith methods. Identical values for net radiation and soil-heat flux were used in each method. Differences between results from the methods are reflected in the calculations of latent-heat flux and sensible-heat flux. During most of mid-summer to fall and all of winter at the Snively Basin site and during late summer to fall at the Turnbull meadow site, the Bowen-ratio estimates could not be made because of poor-quality vapor-pressure data during the summer and fall (due to dry environmental conditions, ice on the DEW-10 mirror, or other environmental instrument anomalies) and lack of vapor-pressure data during the winter (because of the chilled-mirror hygrometer's sensitivity to freezing temperatures). However, sufficient data were collected to enable measurement or calculation of all fluxes necessary for the Penman-Monteith method for the entire period of study. This section discusses the energy-budgets calculated with the Penman-Monteith method for each site.

Instead of repetitive energy-budget plots for the entire period of study for each study site, a series of 6-day plots of the energy-budgets for all four sites for selected periods, representing important conditions such as rainfall, high wind, snow, and dry soil during different times of the year, are presented on figures 11 to 23.

The variability of energy-budget fluxes for different days depended on several conditions: amount and density of cloud cover, rainfall, wind-speed, season of the year, soil-moisture availability, and stage of plant growth. Clear days, such as July 26-28, 1990 (fig. 11), March 30, 1991 (fig. 15), July 20, 1991 (fig. 22), and August 20, 1991 (fig. 22), show smooth net-radiation curves. This smoothness also is generally reflected in the other fluxes. Net radiation on partly cloudy days, such as May 31, July 23-25, and August 8-10, 1990 (figs. 11) and April 2-7, 1991 (fig. 20), exhibits much irregularity due to clouds passing over the site. On completely cloudy days, such as March 24-25, 1991 (fig. 15), and May 16-19, 1991 (fig. 17), net-radiation and other fluxes are low and somewhat irregular, depending on the thickness of the cloud cover. The plots also show strong seasonal differences in net radiation. Net radiation on a clear day in winter (February 5, 1991 on fig. 14) is only 56 percent as much as on a clear day in spring (March 30, 1991 on fig. 15), or 42 percent as much as a clear day in early summer (July 2, 1991 on fig. 18). 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 for all 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. Atmospheric transmittance, surface albedo, and air temperature contributed to the lower net radiation values in winter. Also, during days of snow-cover in winter and early spring (January 7-10, 1991, on fig. 14 and March 25, 1991, on fig. 15), soil-heat flux generally remained low because of the insulating properties of the snow. A rise in the soil-heat flux values (March 26, 1991, on fig. 15), indicated the snow had melted.

During days of precipitation (August 21, 1990, on fig. 12), soil and atmospheric radiation produced little surface warming so that soil and sensible-heat fluxes remained low. Most of the heat energy from net radiation was lost through ET; the latent-heat flux approaches the net-radiation value. Dramatic drops in the fluxes were sometimes noted during late afternoon rainstorms (August 6, 1991, on fig. 19 and June 28, 1991, on fig. 23).

If precipitation was substantial, several days of drying were noted during which latent-heat flux decreased while sensible-heat flux increased (August 21-28, 1990, on fig. 12). In some cases, a cool, cloudy period (June 22-30, 1991, on fig. 18) followed heavy rainfall (June 19-21, 1991, on fig. 17) delaying the maximum latent-heat flux and subsequent drying for several days (June 30 to July 9, 1991, fig. 18).

For periods where the top layer of soil and the air were extremely dry (August 7-12, 1990, on fig. 11, September 25-30, 1990, on fig. 13, and September 14-19, 1991, on fig. 19) most net radiation became sensible-heat flux and, to a lesser extent, soil-heat flux. In this case, sensible-heat flux approached net radiation, while the latent-heat flux approached zero. Exceptions occur during these dry periods when a light rainfall produced a sharp but short increase in latent-heat flux and a decrease in sensible-heat flux (near midnight, August 1, to early morning, August 2, 1991; fig. 19) and near sunset (net radiation near zero), August 6, to early morning, August 7, 1991; fig. 19).

Latent-heat flux can be high in eastern Washington, at many times without precipitation, as a result of plant transpiration and wind-induced evaporation from soil. 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 even in the absence of substantial rainfall for several days (April 29 to May 4 and May 14-15, 1991, on fig. 17). Combinations of plant transpiration and soil evaporation can produce high latent-heat flux at times during the growing season after a heavy rainfall (April 15-22, 1991, on fig. 16 and June 7-11, 1991, on fig. 21). During periods of peak plant growth, some transpiration, as shown in the latent-heat flux values, appears to occur for several hours after sundown (May 21-22, June 8-10, 1991, on fig. 21 and July 18-21, August 15-20, 1991, on fig. 22). During the latter part of the growing season, when plants begin senescing, transpiration gradually decreases, as the decreasing daily latent-heat flux values show (July 31 to September 19, 1991, on fig. 19 and August 15 to September 13, 1991, on fig. 22). High wind can also produce evaporation, even at night (April 3-5, 1991, on fig. 15). The energy source for evaporation during nighttime windy periods is probably soil-heat flux or advected sensible-heat flux.

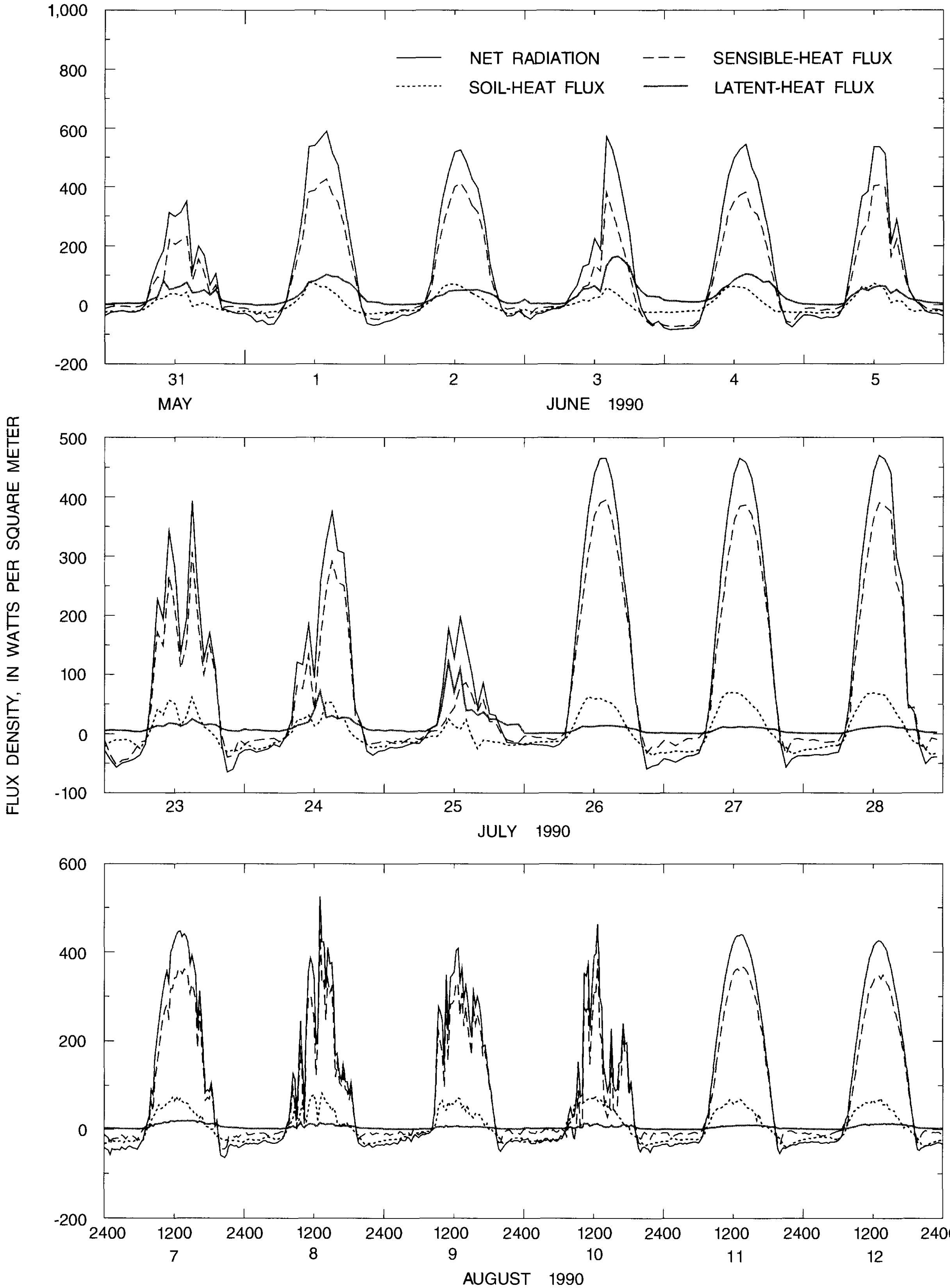

Figure 11.--Energy budget at the Snively Basin site for selected periods from May to August 1990.

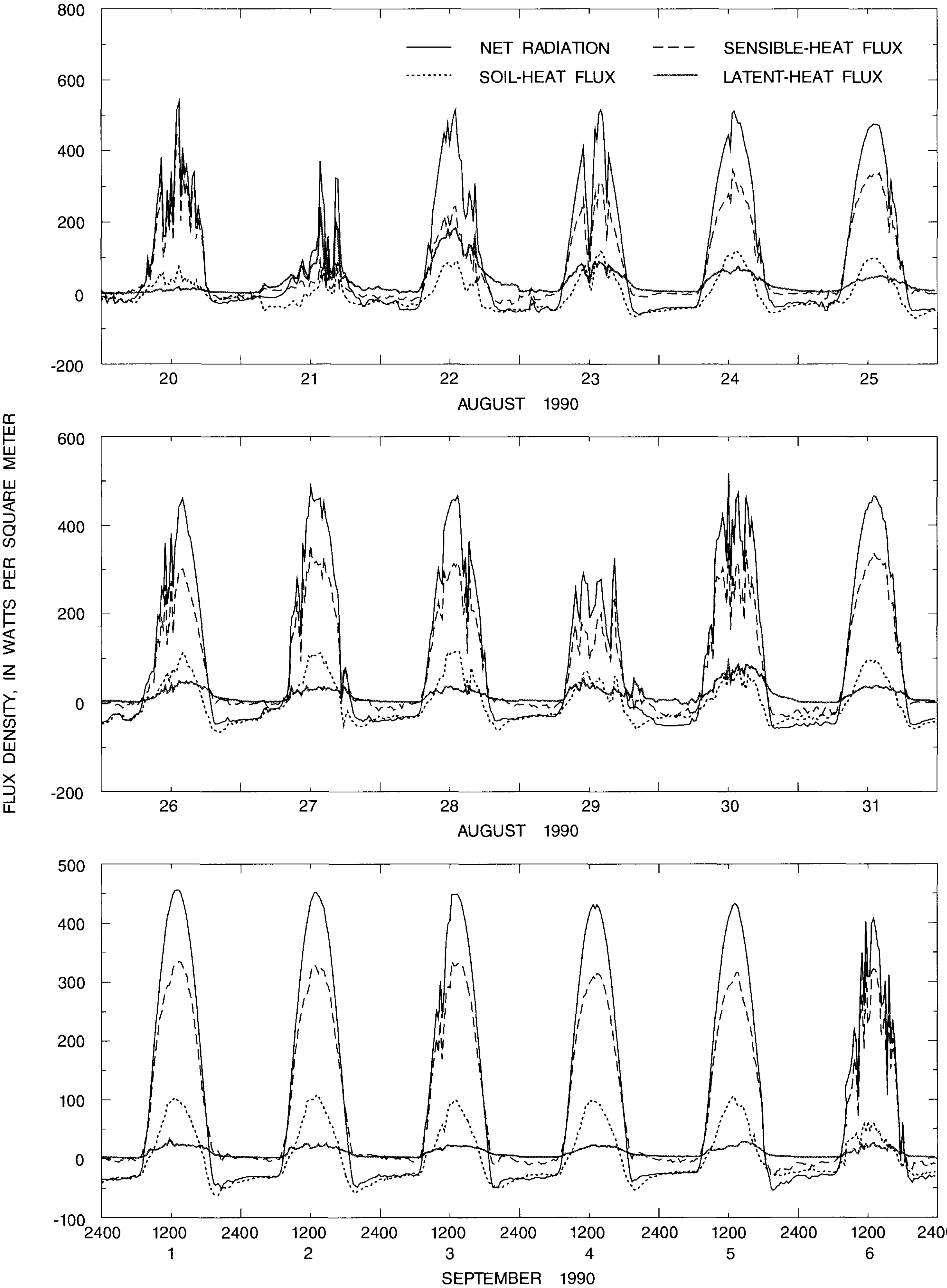

Figure 12.--Energy budget at the Snively Basin site for selected periods from August to September 1990.

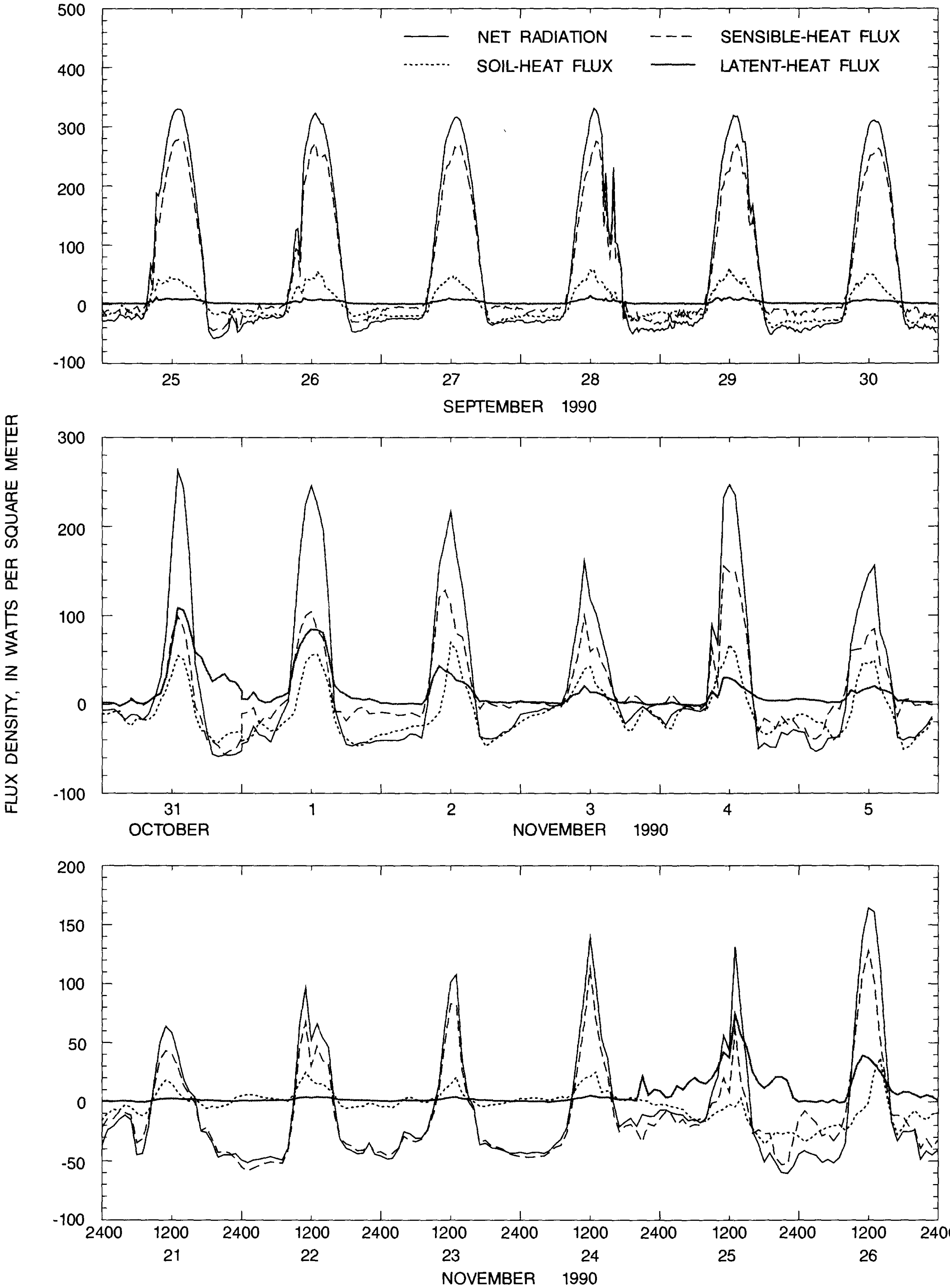

Figure 13.--Energy Budget at Snively Basin site for selected periods from September to November 1990.

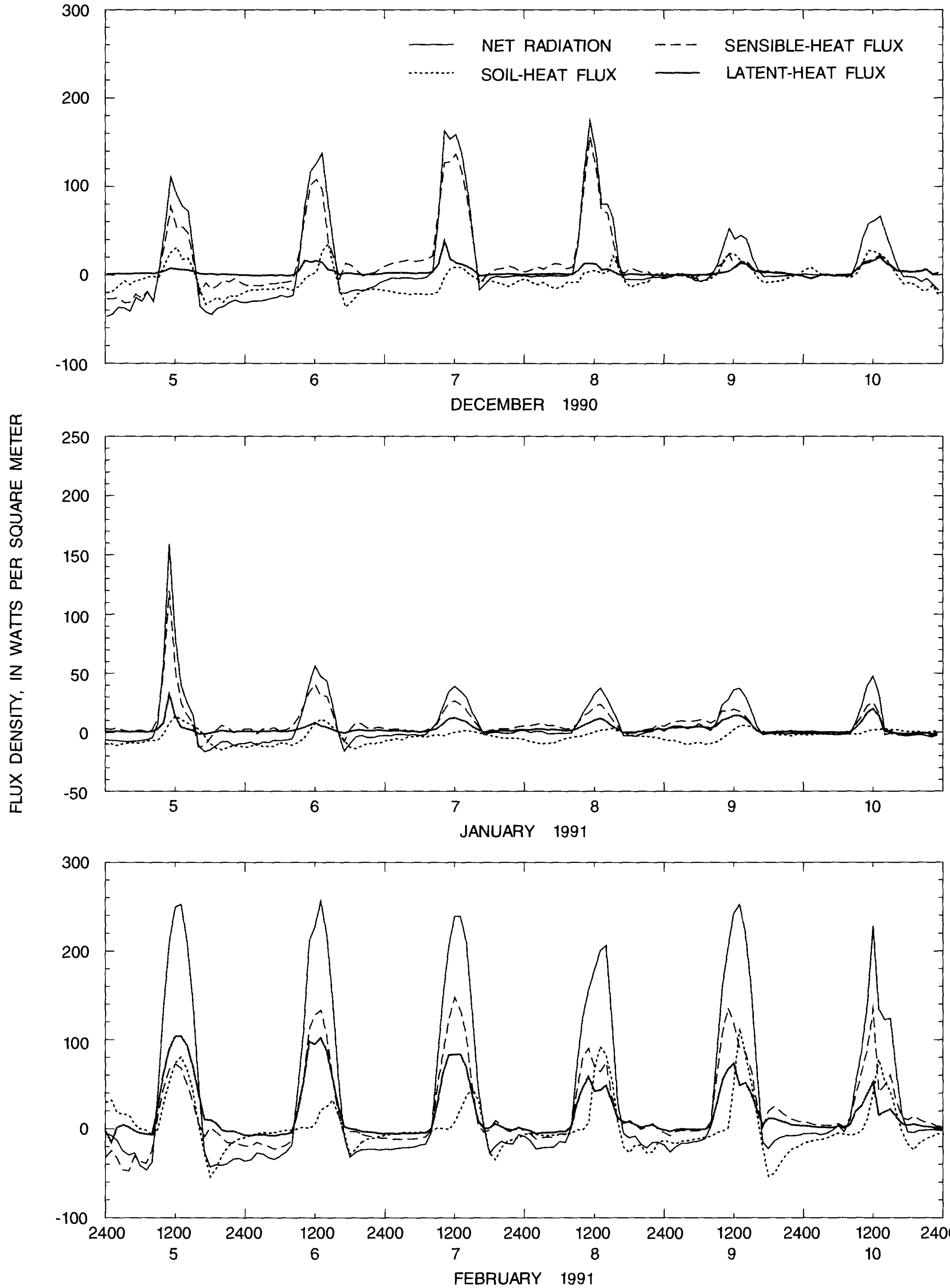

Figure 14.--Energy budget at the Snively Basin site for selected periods from December 1990 to February 1991.

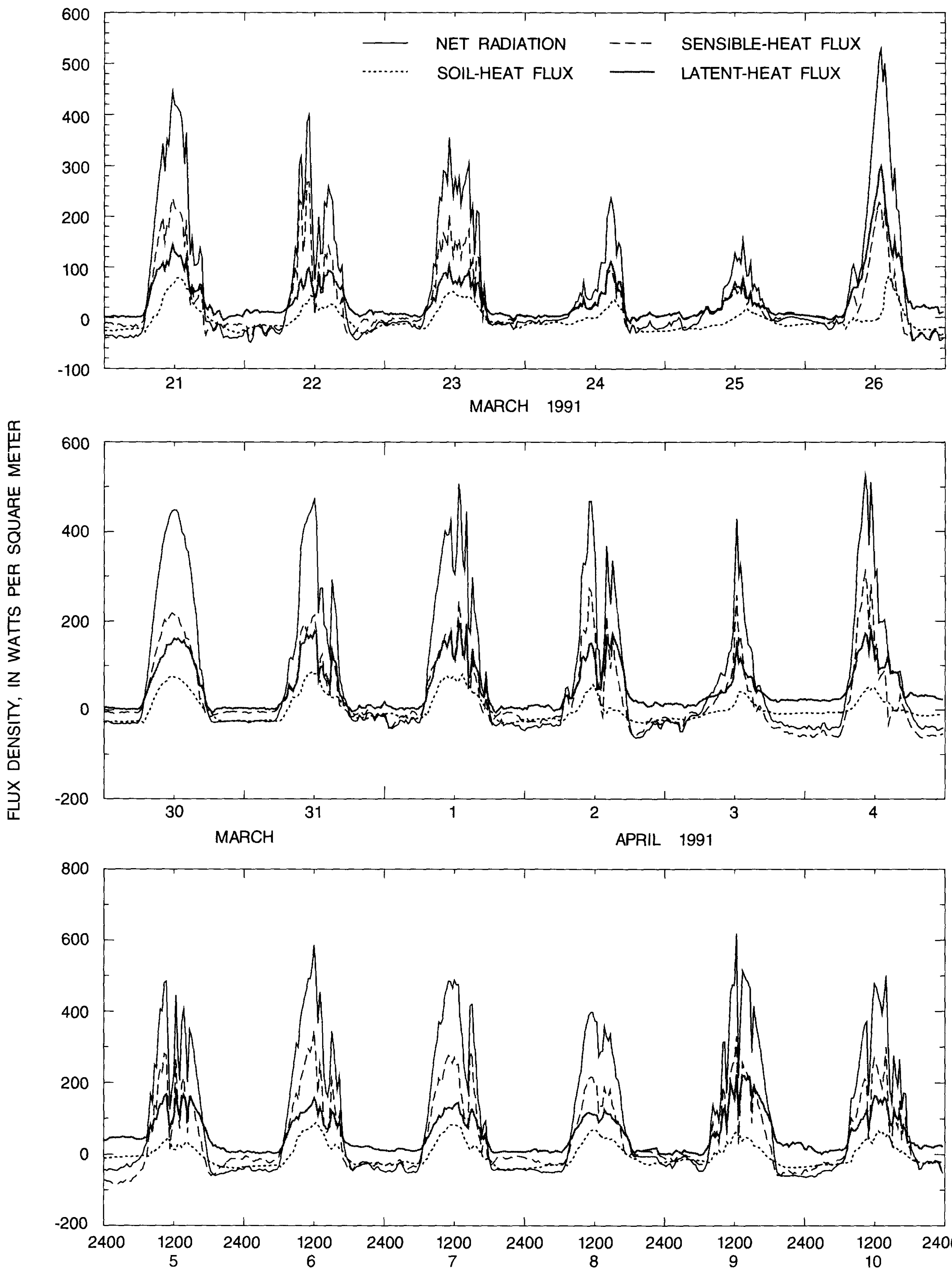

Figure 15.--Energy budget at the Snively Basin site for selected periods from March to April 1991.

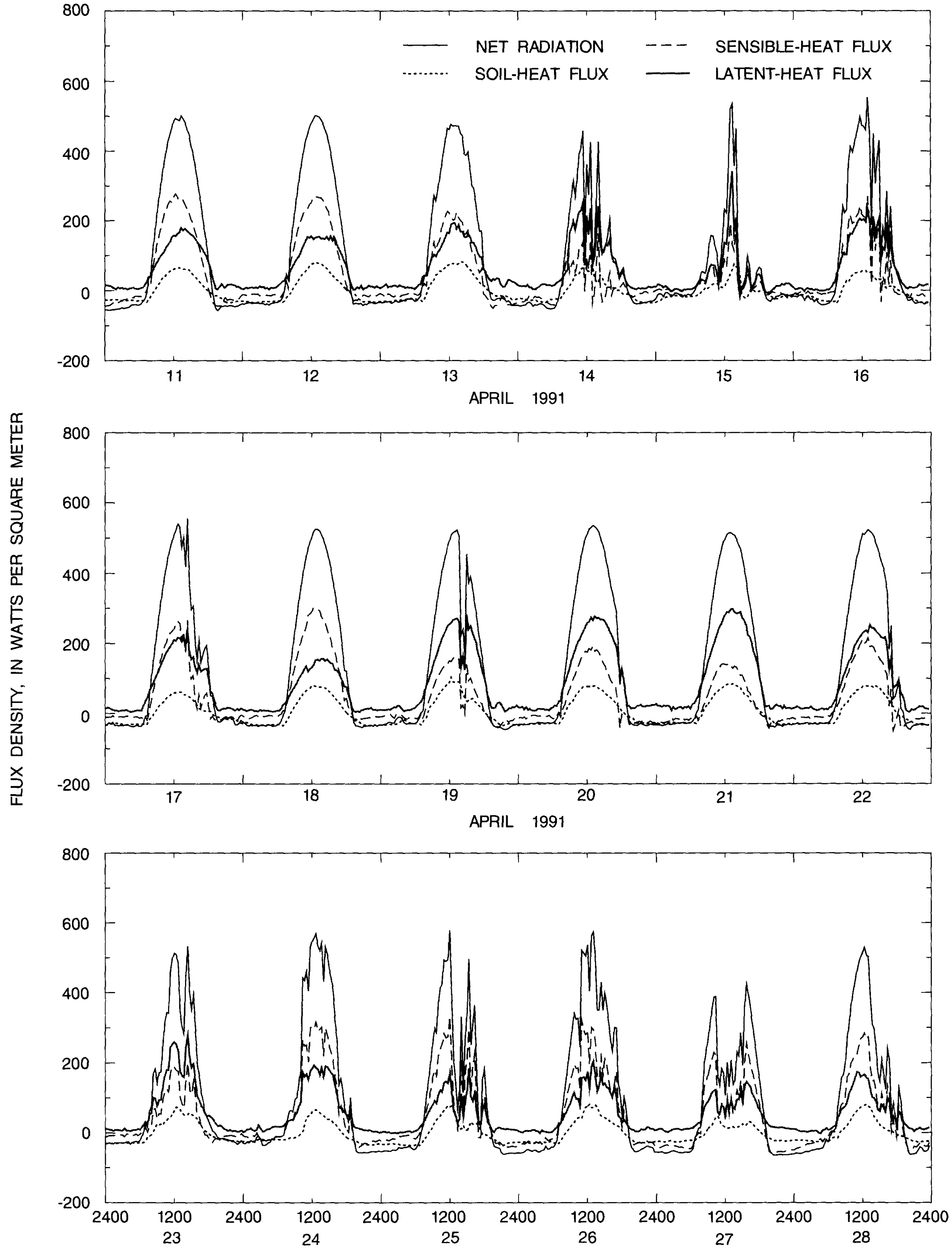

Figure 16.--Energy budget at the Snively Basin site for selected periods in April 1991.

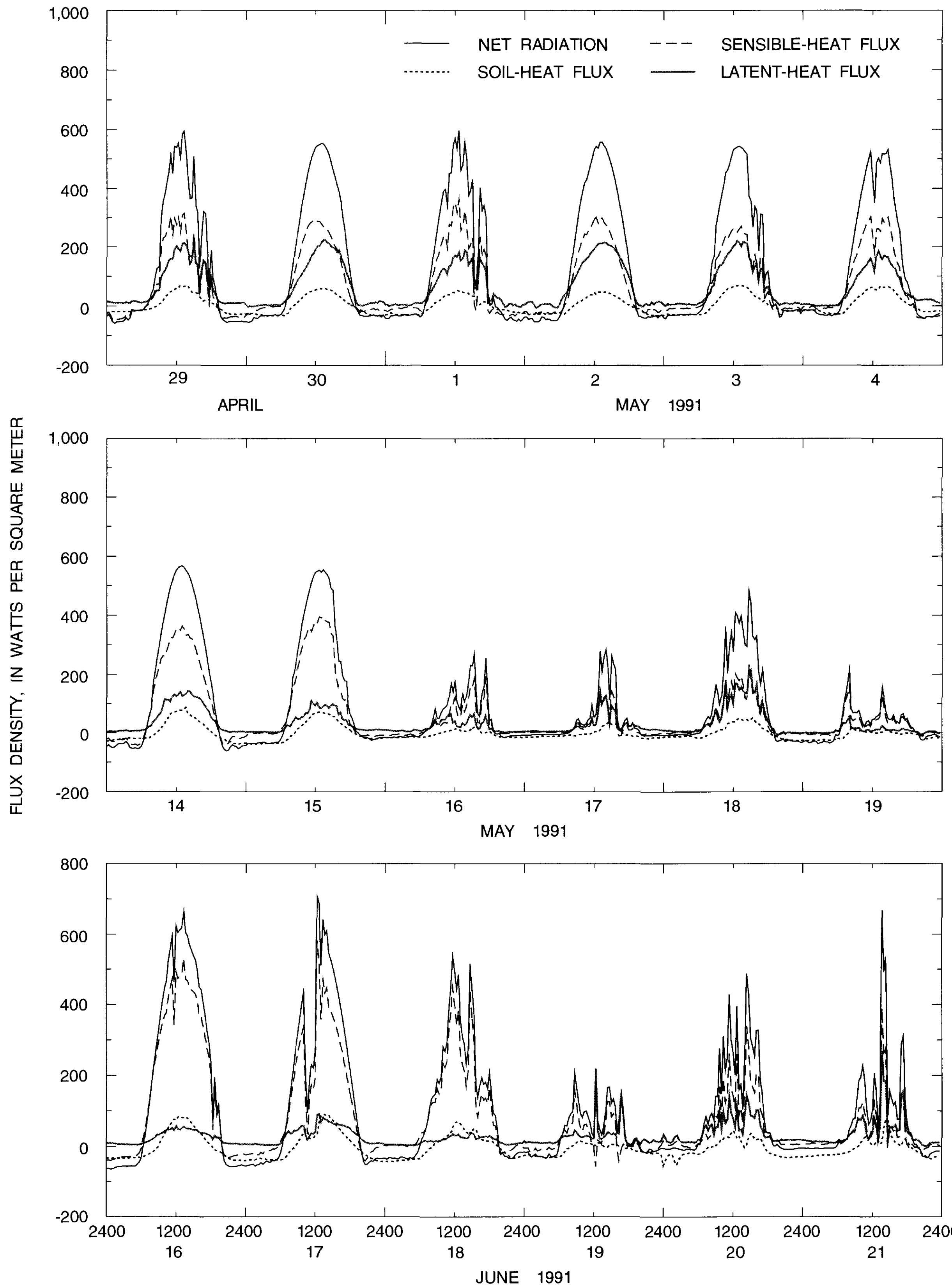

Figure 17.--Energy budget at the Snively Basin site for selected periods from April to June 1991.

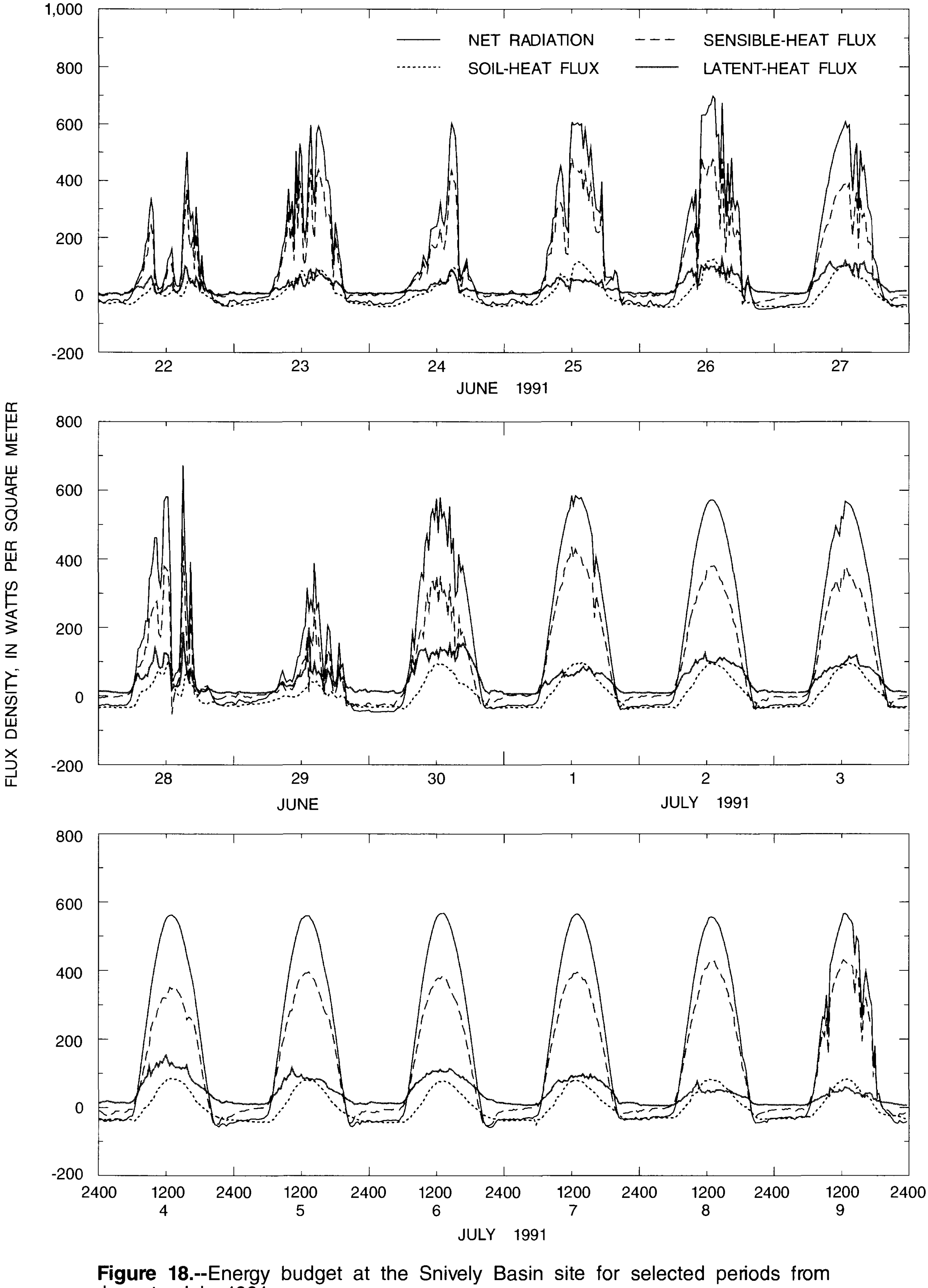

Figure 18.--Energy budget at the Snively Basin site for selected periods from June to July 1991.

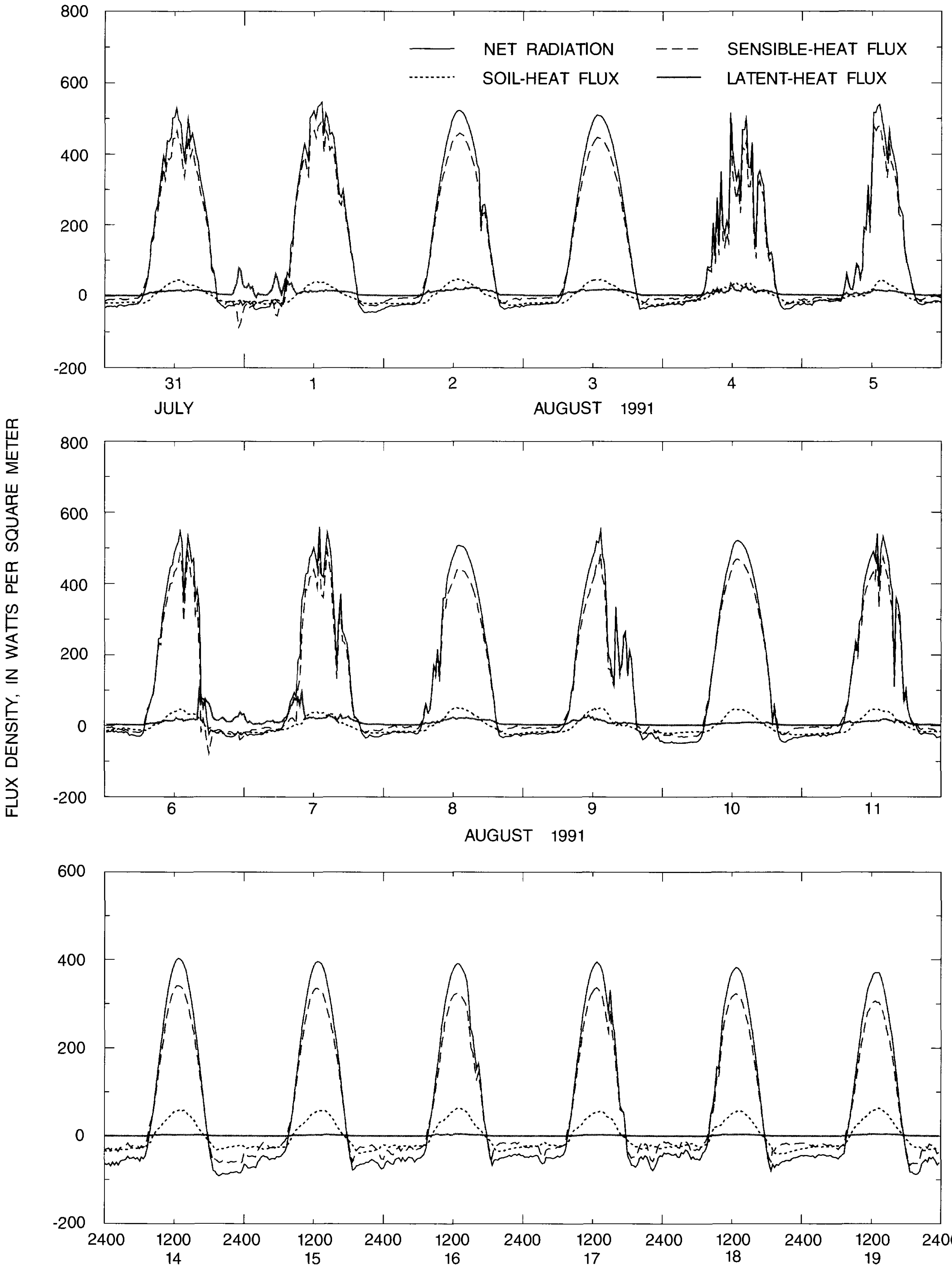

Figure 19.--Energy budget at the Snively Basin site for selected periods from July to September 1991.

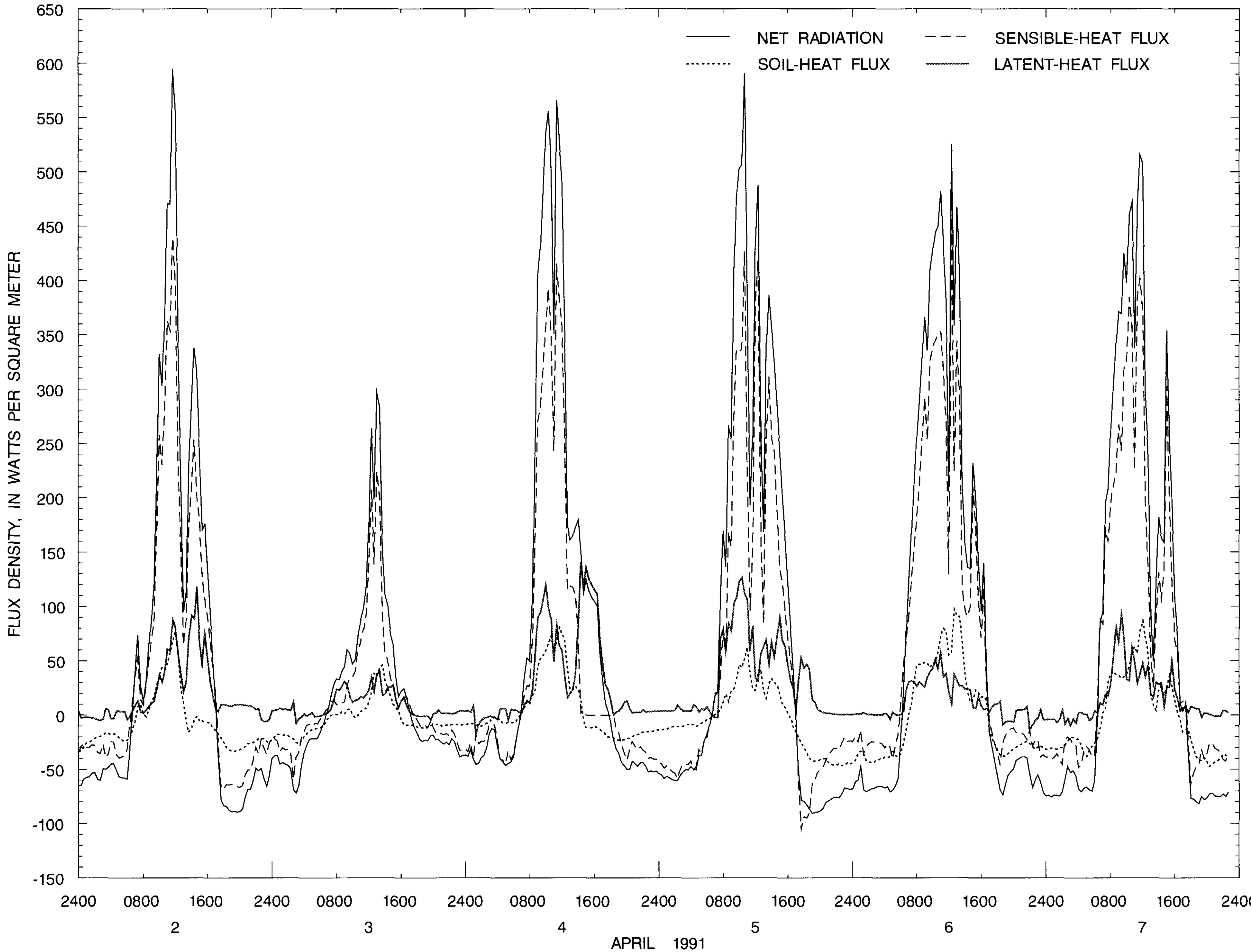

Figure 20.--Energy budget at the grass lysimeter site for April 2-7, 1991.

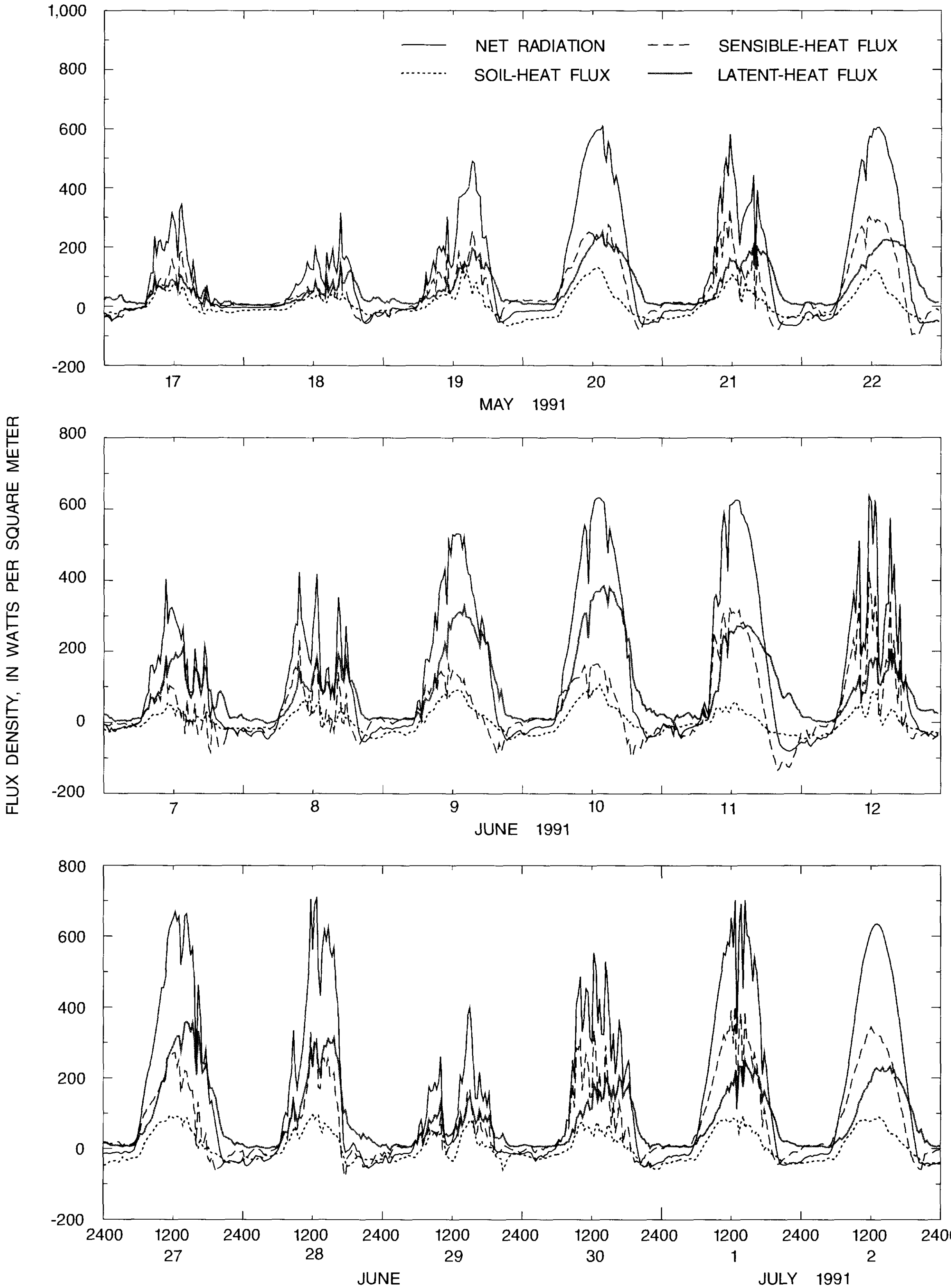

Figure 21.--Energy budget at the Turnbull meadow site for selected periods from May to July 1991.

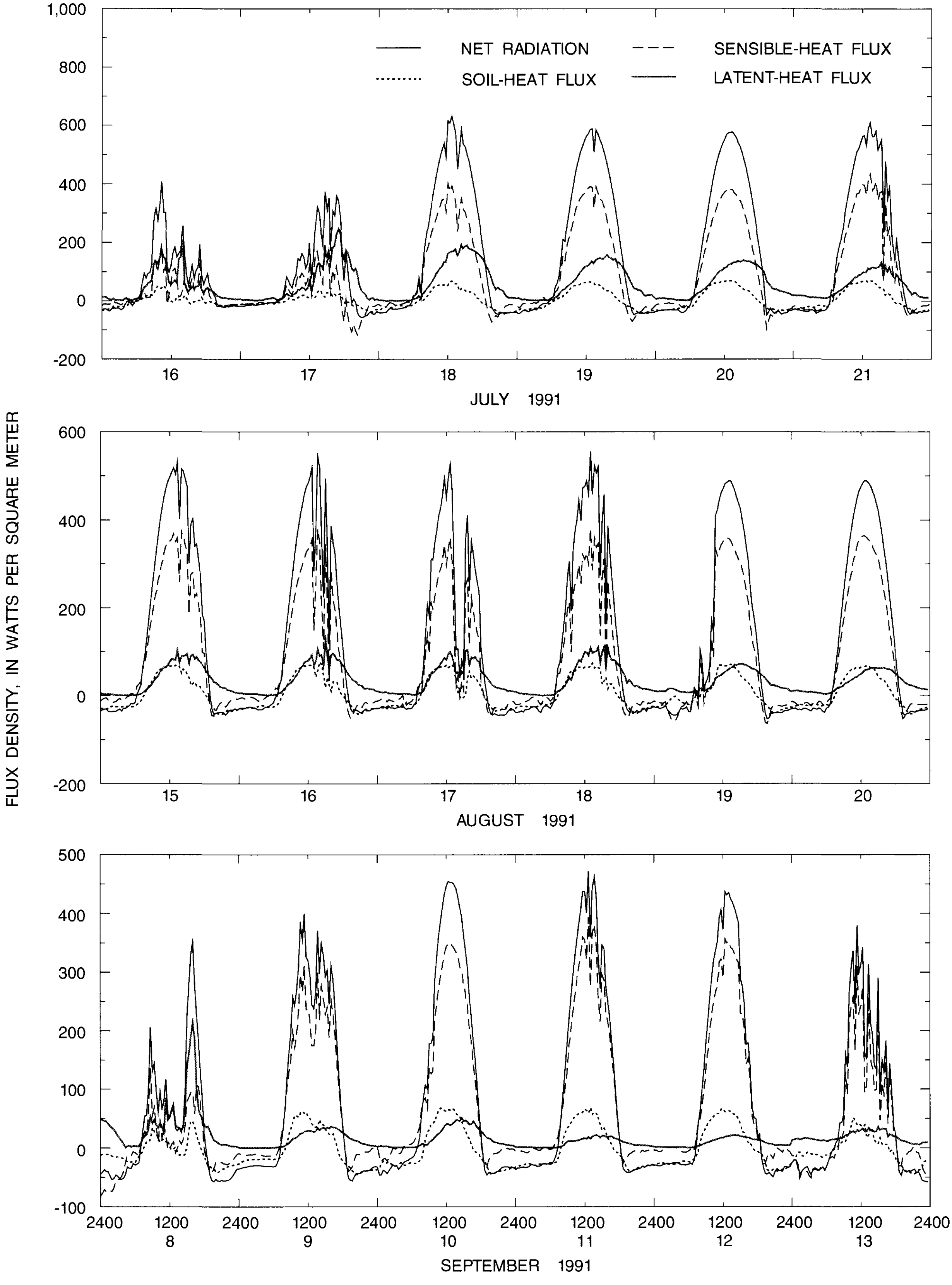

Figure 22.--Energy budget at the Tumbull meadow site for selected periods from July to September 1991.

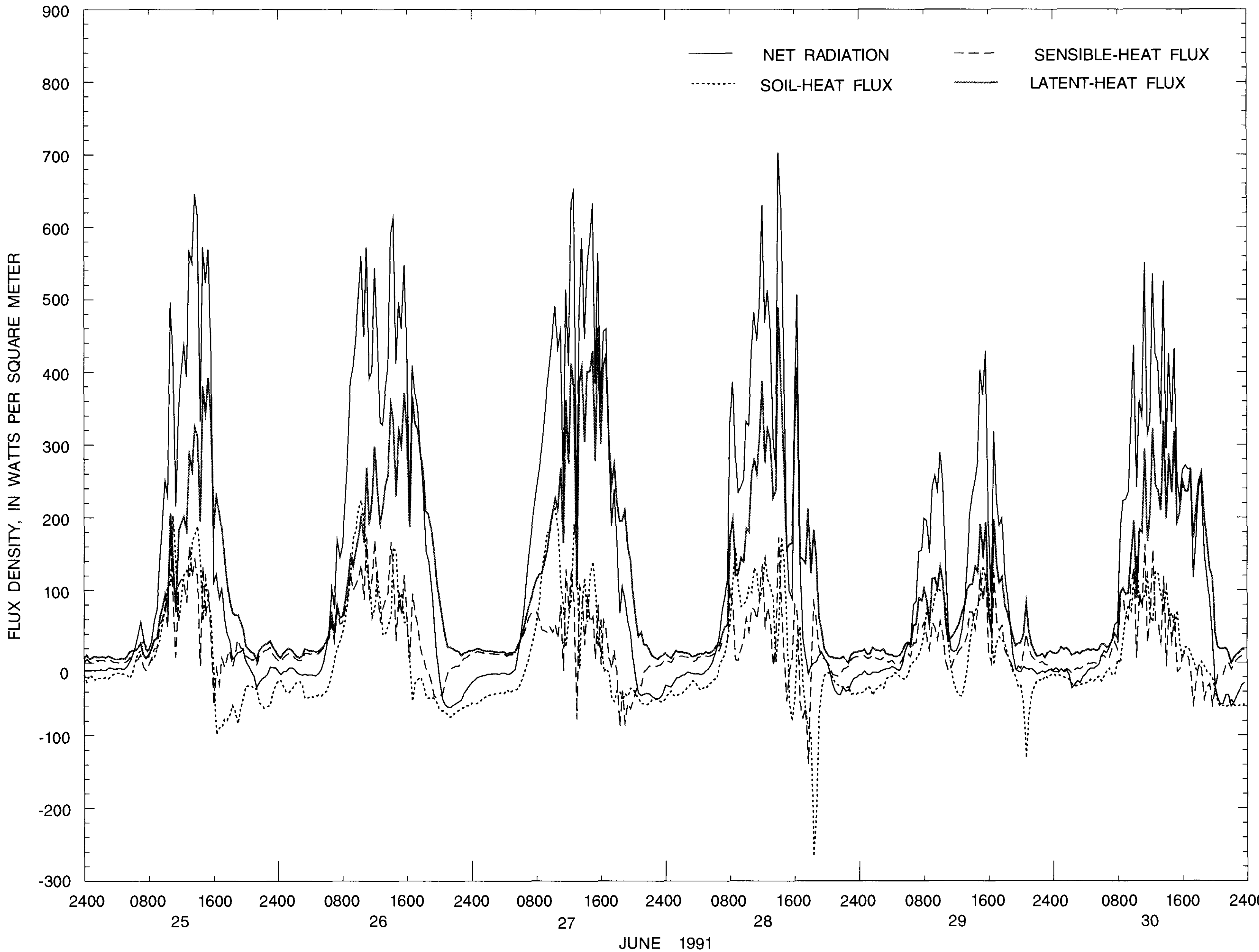

Figure 23.--Energy budget at the Turnbull marsh site, June 25-30, 1991.

Evapotranspiration Estimates

ET estimates were made on the basis of the energy-budget flux calculations made for each site. For the Snively Basin and Turnbull meadow sites, 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 time interval were then averaged for the day. Then, latent-heat flux and ET were recalculated with the Penman-Monteith equation for each time interval using the daily-average canopy resistance. This procedure produced satisfactory estimates of ET with the Penman-Monteith method, compared with ET estimates made with the Bowen-ratio method. For the Snively Basin site, a scatterplot (fig. 24) of daily ET estimates for both methods shows a good correlation; the square of the correlation coefficient, r^2, is 0.97. For the Turnbull meadow site, a similar scatterplot (fig. 24) shows almost as good a correlation between the Bowen-ratio and Penman-Monteith estimated ET's; the square of the correlation coefficient is 0.96. These high squares of the correlation coefficient arise because discrepancies between the two methods really only reflect the effect of averaging the canopy-resistance term for the Penman-Monteith method.

For the grass lysimeter site, ET calculated with the Bowen-ratio method and from weighing-lysimeter data did not compare well. ET estimates were not made with the Penman-Monteith method because its latent-heat fluxes, based on either the Bowen-ratio method or lysimeter data, would be correlated with those two methods; comparisons of ET estimates would thus be meaningless.

For the Turnbull marsh site, potential ET was calculated with the Penman method. No Bowen-ratio data were collected at this site, so canopy resistances for the Penman-Monteith method could not be estimated with the procedure used at the Snively Basin and Turnbull meadow sites. Instead, the correlation between surface soil moisture and canopy resistance made for the Turnbull meadow site was applied to the calculation of ET for the Turnbull marsh site; site conditions at the marsh site were similar to those at the Turnbull meadow site.

Snively Basin Site

Data from the Bowen-ratio method were used to estimate the canopy resistance from May 31 to October 15, 1990, and March 18 to September 30, 1991. From October 16, 1990, to March 17, 1991, canopy resistance estimates were based on environmental conditions such as rainfall, air temperature, relative humidity, and snow cover. ET was generally low (less than 1 millimeter per day) during the late fall and winter (fig. 25 and table 5). The errors in ET estimates on some days probably average out over the season so that the cumulative effect on monthly, seasonal, or annual ET is small.

For May 31, 1990, to September 30, 1991, at the Snively Basin site, daily ET remained generally less than 1 millimeter from mid-summer through fall (fig. 25; table 2). Exceptions to this occurred during and shortly after rainfall (July 25, August 21 and 30, October 18 and 30, and November 25, 1990) when daily ET approached or exceeded 1 millimeter. During the winter, daily ET was low, generally under 0.5 millimeter, because of low net radiation and cold temperatures. Later in winter (February-March, 1991), daily ET rose on mild, sunny days to more than 1 millimeter. During the spring, grasses were at their peak growth and daily ET generally ranged from 1 to 3 millimeters, approaching 4 millimeters on some days (April 20 and 21, 1991). During the early summer, daily ET varied from 0.5 to more than 2 millimeters as the plants matured and began to seed. Days of rain were followed by days of ET greater than 1 millimeter; then, ET gradually decreased until the next rainfall. As summer progressed, the plants senesced, perished, or became dormant and soils dried, reducing daily ET below 0.5 millimeter. Monthly ET varied over the period of study and ranged from less than 2 millimeters during September 1991 to more than 66 millimeters during April 1991 (table 2).

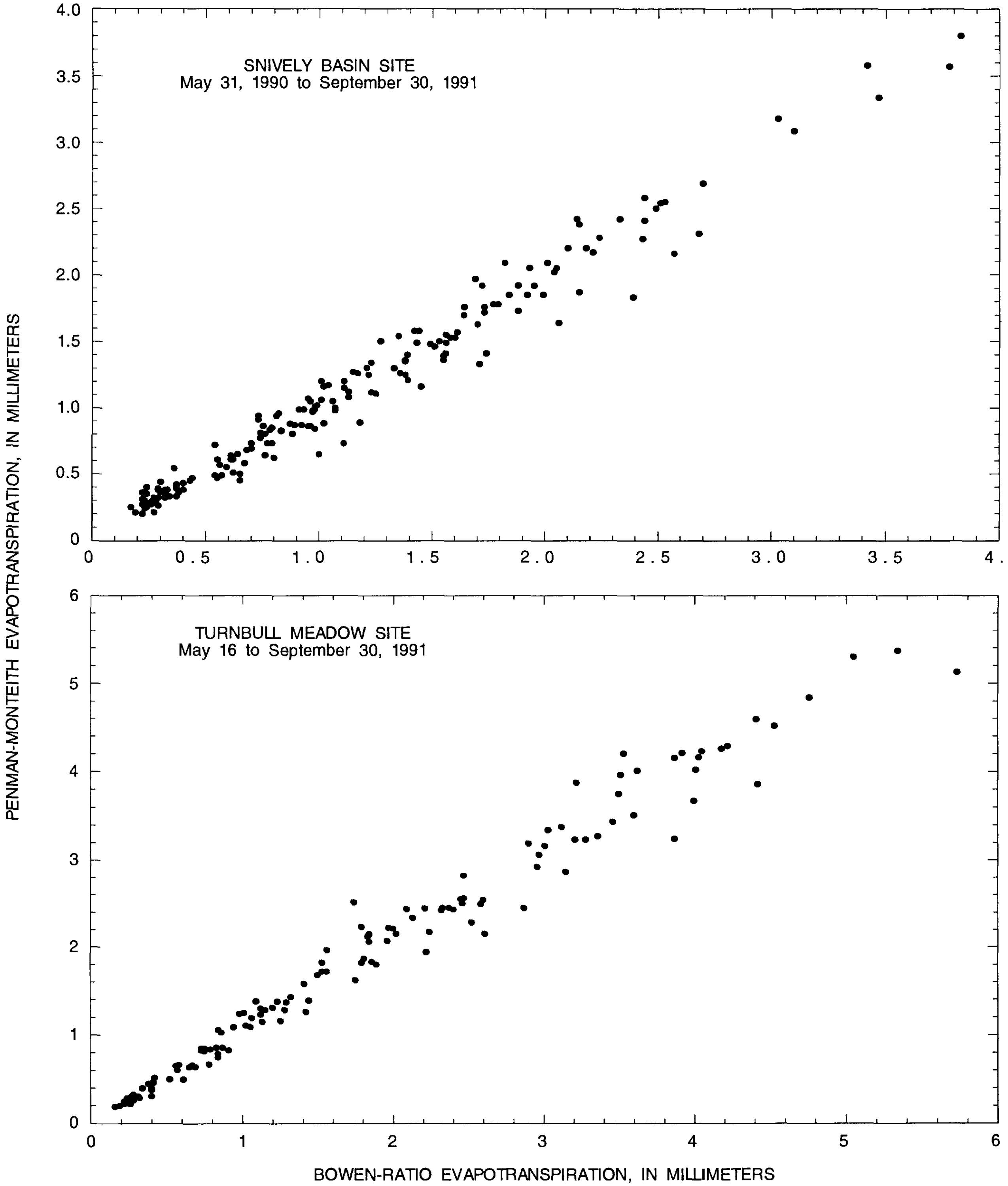

Figure 24.--Bowen-ratio and Penman-Monteith estimates of evapotranspiration for the Snively Basin site, May 31, 1990 to September 30, 1991 and the Turnbull meadow site, May 16 to September 30, 1991.

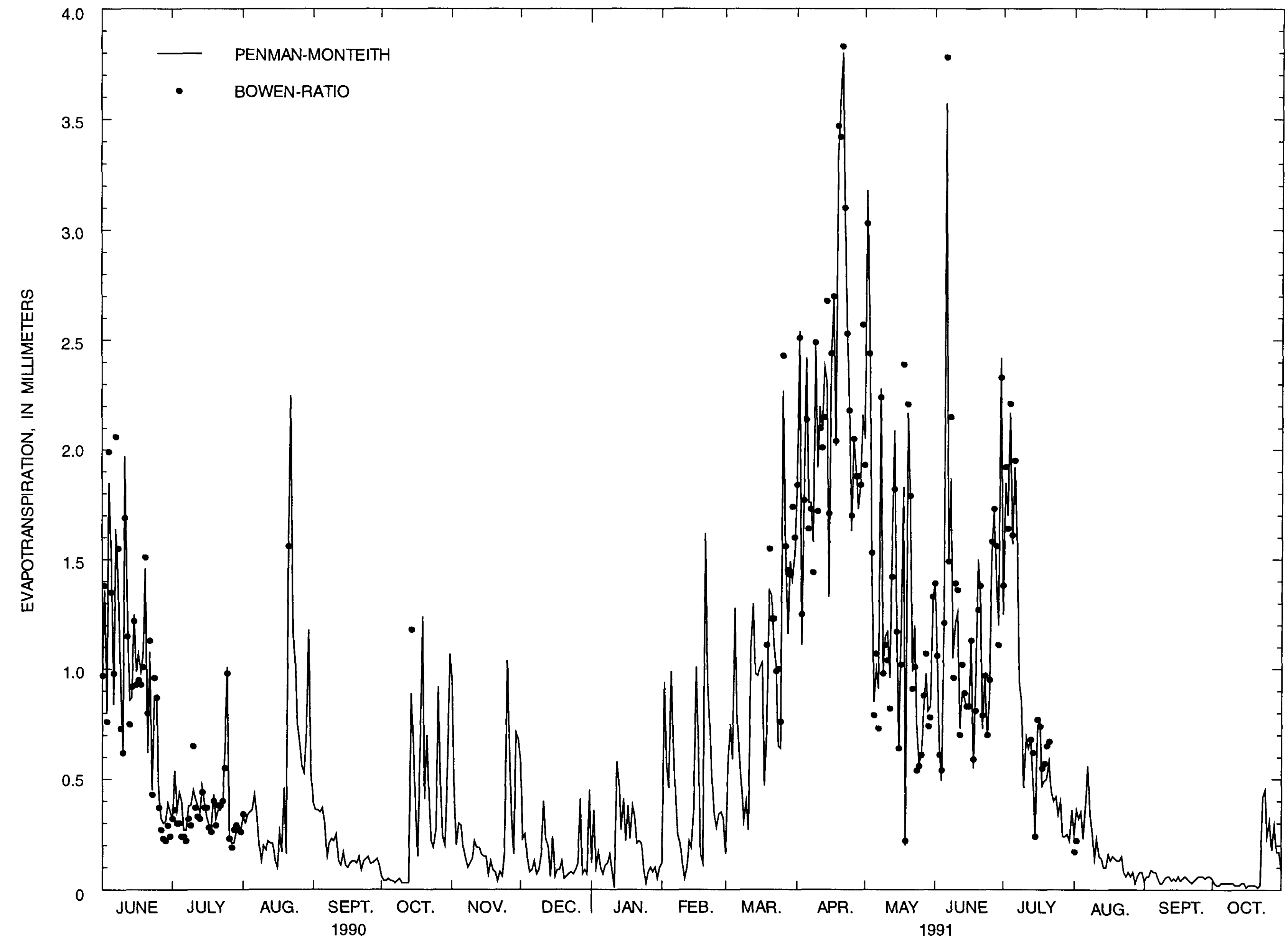

Figure 25.--Evapotranspiration estimated with the Bowen-ratio and Penman-Monteith methods for the Snively Basin site, May 31, 1990 to September 30, 1991.

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991*

[PRC, precipitation; BR, evapotranspiration, Bowen-ratio method; PM, evapotranspiration, Penman-Monteith method; RC, canopy resistance; TOT, monthly totals of daily precipitation and evapotranspiration; TR, data suggest trace of precipitation; mm, millimeter; s/m, seconds per meter; NA, not applicable; --, daily or monthly value not calulated; #, total for June 1990; *, partly estimated or estimated]

	May-June 1990				July 1990				August 1990			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
May												
31	0.51	0.97	0.98	453								
June												
1	0.00	1.38	1.36	523	0.00	0.32*	0.32	4,890	0.00	0.36	0.33	8,970
2	.00	.76	.80	1,400	1.52	.36*	.54	3,680	.00	--	.30	8,400
3	.00	1.99	1.85	274	.00	.30*	.36	4,160	.00	--	.34	7,210
4	.00	1.35	1.54	546	.00	.30*	.44	4,370	.00	--	.35	8,500
5	.00	.98	.84	1,180	.00	.24*	.40	4,630	.00	--	.36	9,860
6	6.60	2.06	1.64	126	.00	.24*	.27	4,660	.00	--	.43	7,540
7	.00	1.55	1.39	663	.00	.22*	.27	6,380	.00	--	.34	8,060
8	.00	.73	.94	771	.00	.32*	.38	5,870	.00	--	.21	14,900
9	.00	.62	.61	2,587	.00	.29*	.38	7,690	.00	--	.13	23,400
10	1.27	1.69	1.97	342	.00	.65*	.45	6,490	.00	--	.20	13,000
11	.00	1.15	1.27	529	.00	.37	.41	10,200	.00	--	.18	14,300
12	.00	.75	.86	800	.00	.33	.38	10,400	.00	--	.22	13,200
13	.00	.92	.87	928	.00	.32	.35	10,200	.00	--	.21	13,700
14	.00	1.22	1.25	790	.00	.44	.47	6,880	.00	--	.21	11,000
15	.00	.93	.99	1,620	.00	.37	.39	9,370	.00	--	.13	12,300
16	.00	.95	1.07	1,390	.00	.37	.33	8,840	.00	--	.10	16,100
17	.00	.93	.99	1,260	.00	.28	.29	9,800	TR	--	.26	2,910
18	.00	1.01	1.06	1,420	.00	.26	.29	10,000	.00	--	.17	6,020
19	.51	1.51	1.46	1,080	.00	.40	.43	6,370	TR	--	.46	1,100
20	.00	.80	.62	2,120	.00	.29	.32	9,010	.00	--	.16	6,420
21	.00	1.13	1.08	1,830	.00	.38	.36	8,250	28.19	1.56*	1.49	80.2*
22	.00	.43	.45	3,260	.00	.38	.36	9,310	.00	--	2.30	321 *
23	.00	.96	.86	2,130	.00	.40	.38	5,610	.00	--	1.17	1,000 *
24	.00	.87	.88	2,480	TR	.55	.61	2,310	.00	--	1.04	1,240 *
25	.00	.37*	.42	5,820	1.27	.98	1.01	605	.00	--	.74	1,400 *
26	.00	.27*	.32	5,940	.00	.23	.24	8,540	.00	--	.66	1,660 *
27	.00	.23*	.30	5,670	.00	.19	.21	10,300	.00	--	.56	3,010 *
28	.00	.22*	.31	5,240	.00	.27	.21	10,300	.00	--	.53	4,120 *
29	.00	.29*	.39	6,560	.00	.29	.26	10,500	.00	--	.72	2,390 *
30	.00	.24*	.35	5,260	.00	.27	.29	8,670	3.56	--	1.18	678 *
31					.00	.26	.27	9,980	.00	--	.54	2,670 *
TOT	8.38#	28.29	28.74	NA	2.79	10.87	11.67	NA	31.75	--	16.02	NA

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991--Continued*

	September 1990				October 1990				November 1990			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	0.00	--	0.37	5,860 *	0.00	--	0.04	23,500	0.00	--	0.94	200 *
2	.00	--	.35	6,390 *	.00	--	.03	23,100	.00	--	.40	500 *
3	.00	--	.21	8,760*	.00	--	.03	29,200	.00	--	.20	800 *
4	.00	--	.24	10,700 *	.00	--	.02	35,400	.00	--	.30	1,000 *
5	.00	--	.28	10,600 *	.00	--	.02	38,100	.00	--	.29	1,000 *
6	.00	--	.28	10,000 *	.00	--	.02	41,000	.00	--	.19	2,000 *
7	.00	--	.15	11,700	.00	--	.02	41,000	.00	--	.14	2,000 *
8	.00	--	.23	12,200	.00	--	.02	41,000	.00	--	.10	2,000 *
9	.00	--	.22	12,500	.00	--	.02	41,500	.00	--	.12	2,000 *
10	.00	--	.20	14,200	.00	--	.02	41,600	.00	--	.14	2,000 *
11	.00	--	.24	12,500	.00	--	.02	41,700	.00	--	.22	2,000 *
12	.00	--	.16	12,000	.00	--	.02	42,300	.00	--	.19	2,000 *
14	.00	--	.18	12,000	2.29	1.18	.89	71.8	.00	--	.16	2,000 *
15	.00	--	.10	11,800	.00	--	.65	629	.00	--	.15	2,000 *
16	.00	--	.11	12,000	.00	--	.35	1,000 *	.00	--	.15	2,000 *
17	.00	--	.14	12,000	.00	--	.15	2,000 *	.00	--	.07	2,000 *
18	.00	--	.14	12,000	6.35	--	.64	100 *	.00	--	.13	2,000 *
19	.00	--	.15	12,000	.00	--	1.24	500 *	.00	--	.09	2,000 *
20	.00	--	.13	12,000	.00	--	.41	1,000 *	.00	--	.08	2,000 *
21	.00	--	.17	12,000	1.02	--	.70	200 *	.00	--	.04	3,000 *
22	.00	--	.17	11,300	.00	--	.42	1,000 *	.00	--	.08	3,000 *
23	.00	--	.14	17,100	.00	--	.22	2,000 *	.00	--	.06	3,000 *
24	.00	--	.14	18,900	.00	--	.19	3,000 *	.25	--	.17	3,000 *
25	.00	--	.10	20,700	3.05	--	.27	3,000 *	2.03	--	1.04	100 *
26	.00	--	.14	13,700	.00	--	.92	200 *	.00	--	.68	200 *
27	.00	--	.10	19,100	.00	--	.45	1,000 *	.00	--	.35	500 *
28	.00	--	.13	15,000	.00	--	.24	2,000 *	.00	--	.16	1,000 *
29	.00	--	.12	19,500	2.03	--	.20	3,000 *	1.52	--	.71	1,000 *
30	.00	--	.07	24,000	14.22	--	.55	0 *	.00	--	.68	200 *
31					.51	--	1.07	100 *				
TOT	0.00	--	5.30	NA	29.47	--	9.85	NA	3.80	--	8.22	NA

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991--Continued*

	December 1990				January 1991				February 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	0.25	--	0.58	100 *	0.00	--	0.12	100 *	0.00	--	0.12	2,000 *
2	.00	--	.23	500 *	.00	--	.36	200 *	2.03	--	.94	0 *
3	.00	--	.25	1,000 *	.00	--	.10	500 *	.76	--	.58	100 *
4	.00	--	.14	2,000 *	.00	--	.17	1,000 *	2.03	--	.46	100 *
5	.00	--	.08	2,000 *	.00	--	.10	1,000 *	2.79	--	.99	100 *
6	.00	--	.09	2,000 *	.76	--	.07	0 *	.00	--	.66	200 *
7	.00	--	.13	2,000 *	1.78	--	.11	0 *	.00	--	.43	500 *
8	.00	--	.07	2,000 *	.00	--	.12	0 *	.00	--	.25	1,000 *
9	5.59	--	.09	0 *	2.29	--	.16	0 *	.00	--	.21	2,000 *
10	8.64	--	.16	0 *	1.52	--	.08	0 *	.00	--	.12	2,000 *
11	.00	--	.40	100 *	7.88	--	.01	0 *	.00	--	.05	2,000 *
12	.00	--	.23	200 *	.25	--	.58	0 *	1.27	--	.10	2,000 *
13	.00	--	.20	500 *	.25	--	.49	100 *	2.79	--	.22	0 *
14	.00	--	.06	800 *	.51	--	.27	100 *	.00	--	.19	100 *
15	.00	--	.24	1,000 *	.25	--	.41	100 *	.25	--	.36	100 *
16	.00	--	.06	2,000 *	.25	--	.22	100 *	.00	--	1.01	200 *
17	.00	--	.09	2,000 *	.00	--	.38	100 *	.00	--	.66	500 *
18	1.27	--	.09	0 *	.25	--	.23	100 *	.00	--	.16	1,000 *
19	2.79	--	.13	0 *	.00	--	.38	100 *	.00	--	.12	2,000 *
20	.00	--	.05	0 *	.00	--	.33	200 *	.76	--	1.62	100 *
21	1.78	--	.06	0 *	.00	--	.21	500 *	.00	--	.94	200 *
22	.00	--	.07	0 *	.00	--	.22	800 *	.00	--	.76	500 *
23	.00	--	.08	0 *	.00	--	.21	1,000 *	.00	--	.52	1,000 *
24	.00	--	.07	0 *	.00	--	.09	2,000 *	.00	--	.34	2,000 *
25	.00	--	.09	0 *	.00	--	.03	2,000 *	.00	--	.28	2,000 *
26	.25	--	.12	0 *	.00	--	.08	2,000 *	.00	--	.34	2,000 *
27	.00	--	.41	0 *	.00	--	.10	2,000 *	.00	--	.35	2,000 *
28	3.56	--	.07	0 *	.00	--	.08	2,000 *	.00	--	.32	2,000 *
29	.25	--	.09	0 *	.00	--	.10	2,000 *				
30	1.78	--	.07	0 *	.00	--	.05	2,000 *				
31	1.78	--	.45	0 *	.00	--	.10	2,000 *				
TOT	27.94	--	4.95	NA	15.99	--	5.96	NA	12.68	--	13.10	NA

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991--Continued*

	March 1991				April 1991				May 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	0.51	--	0.16	0 *	0.00	1.84	1.85	309	0.00	1.93	2.05	302
2	9.91	--	.58	0 *	.51	2.51	2.54	95.0	.TR	3.03	3.18	190
3	7.11	--	.75	0 *	.00	1.25	1.11	249	.00	2.44	2.58	266
4	5.08	--	.59	0 *	4.32	1.77	1.78	232	.00	1.53	1.50	784
5	.00	--	1.28	200 *	.00	2.14	2.42	125	.00	.79	.85	854
6	.00	--	.79	500 *	.00	1.64	1.76	190	TR	1.07	1.00	665
7	.00	--	.63	800 *	.00	1.73	1.76	203	2.54	.73	.91	429
8	.00	--	.48	1,000 *	5.84	1.44	1.58	163	2.54	2.24	2.28	188
9	.00	--	.31	1,000 *	.51	2.49	2.50	84.9	.00	.98	.99	458
10	.00	--	.40	1,000 *	.00	1.72	1.92	155	.00	1.11	1.15	545
11	1.27	--	.27	100 *	.00	2.10	2.20	250	.00	1.04	1.17	567
12	2.54	--	1.10	0 *	.00	2.01	2.09	285	.25	.82	.96	593
13	.00	--	1.30	100 *	.00	2.15	2.38	299	.00	1.42	1.58	395
14	.00	--	.98	200 *	TR	2.68	2.31	49.8	.00	1.82	2.09	515
15	.00	--	.97	300 *	6.10	1.71	1.33	34.1	.00	1.17	1.26	929
16	.00	--	1.01	400 *	.00	2.44	2.41	143	4.06	.64	.65	432
17	.00	--	1.03	500 *	.00	2.70	2.69	153	3.81	1.02	1.16	64.1
18	.51	--	.47	100 *	.00	2.04	2.02	321	.76	2.39	1.83	113
19	.51	1.11	.73	160	.00	3.47	3.34	122	.00	.22	.20	980
20	.00	1.55	1.36	218	.00	3.42	3.58	166	.00	2.21	2.17	459
21	.00	1.23	1.34	281	.00	3.83	3.80	172	.00	1.79	1.78	917
22	.00	1.23	1.12	197	.00	3.10	3.09	219	.00	.91	.99	1,760
23	.00	.99	1.02	238	.00	2.53	2.55	192	.00	1.01	1.20	1,200
24	10.92	1.00	.65	0	.25	2.18	2.20	157	.00	.54	.72	1,270
25	4.06	.76	.64	0	.00	1.70	1.63	358	.00	.56	.57	1,740
26	4.57	2.43	2.27	0	.00	2.05	2.05	235	.00	.61	.61	2,040
27	.00	1.56	1.55	218	.00	1.88	1.92	265	.00	.88	.80	1,640
28	.00	1.45	1.16	244	.00	1.88	1.73	316	.00	1.07	.98	1,490
29	.00	1.43	1.49	275	.00	1.84	1.85	444	.00	.74	.81	953
30	.00	1.74	1.41	381	.00	2.57	2.16	323	.00	.78	.83	1,230
31	.00	1.60	1.53	339					.00	1.33	1.30	1,200
TOT	46.99	--	29.37	NA	17.53	66.81	66.55	NA	13.96	38.82	40.15	NA

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991--Continued*

	June 1991				July 1991				August 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	0.00	1.39	1.40	1,410	0.00	1.38	1.25	1,700	0.00	--	0.25	10,200
2	.00	1.06	1.05	1,910	.00	1.92	1.85	1,610	.00	--	.36	8,440
3	.00	.61	.64	1,690	.00	1.64	1.70	2,330	.00	--	.32	10,500
4	.00	.54	.49	2,680	.00	2.21	2.17	1,430	.00	--	.35	9,440
5	7.37	1.21	1.30	328	.00	1.61	1.57	1,670	.00	--	.23	8,900
6	6.10	3.78	3.57	36.2	.00	1.95	1.92	1,010	.76	--	.60	7,930
7	.00	1.49	1.48	606	.00	--	1.58	1,360	.25	--	.70	5,940
8	.00	2.15	1.87	660	.00	--	.94	3,450	.00	--	.34	9,730
9	.00	.96	1.05	1,880	.00	--	.85	3,190	.00	--	.26	10,200
10	.00	1.39	1.21	2,060	.00	--	.46	5,330	.00	--	.14	11,000
11	.00	1.36	1.26	1,010	.00	--	.69	4,250	.00	--	.23	7,810
12	.00	.70	.73	1,350	.00	--	.64	5,560	.00	--	.15	12,800
13	1.02	1.02	.88	1,120	.51	.68	.68	5,480	.00	--	.14	12,900
14	.00	.89	.87	1,410	.00	.62	.51	3,840	.00	--	.10	20,900
15	.00	.83	.82	1,660	.00	.24	.25	5,310	.00	--	.10	26,800
16	.00	.83	.83	1,070	1.27	.77	.73	1,790	.00	--	.16	20,600
17	.00	1.13	1.12	1,200	TR	.74	.77	1,920	.00	--	.13	23,800
18	.00	.59	.55	2,530	.00	.55	.47	4,410	.00	--	.15	25,000
19	7.11	.81	.94	1,140	.00	.57	.49	4,810	.00	--	.14	25,600
20	21.08	1.27	1.50	105	.00	.65	.50	4,880	.00	--	.13	28,400
21	1.52	1.38	1.35	149	.00	.67	.58	4,390	.00	--	.13	28,300
22	TR	0.79	.73	792	.00	--	.44	6,320	.00	--	.15	21,400
23	.00	.97	.97	1,340	.00	--	.40	7,510	.00	--	.08	31,200
24	.00	.70	.69	1,490	.00	--	.42	7,780	.00	--	.06	33,500
25	.00	.95	.86	2,020	.00	--	.34	5,430	.00	--	.08	24,400
26	.00	1.58	1.53	956	.00	--	.40	5,680	.00	--	.06	30,700
27	.00	1.73	1.72	963	.00	--	.24	10,200	.00	--	.08	18,600
28	.00	1.56	1.41	1,180	.00	--	.24	11,130	.00	--	.03	23,300
29	.25	1.11	1.20	452	.00	--	.25	10,600	.00	--	.06	28,900
30	TR	2.33	2.42	499	.00	--	.22	11,700	.00	--	.08	28,300
31					.51	--	.41	10,800	.00	--	.08	24,600
TOT	44.45	37.11	36.44	NA	2.29	--	23.91	NA	1.01	--	5.87	NA

Table 2.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Snively Basin site, May 31, 1990 to September 30, 1991--Continued*

	September 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	0.00	--	0.04	29,800
2	.00	--	.06	30,000 *
3	.00	--	.06	30,000 *
4	.00	--	.09	30,000 *
5	.00	--	.08	30,000 *
6	.00	--	.08	29,700
7	.00	--	.05	30,000 *
8	.00	--	.03	30,000 *
9	.00	--	.03	30,000 *
10	.00	--	.05	30,000 *
11	.00	--	.06	30,000 *
12	.00	--	.06	30,000 *
13	.00	--	.04	30,000 *
14	.00	--	.05	30,000 *
15	.00	--	.04	30,000 *
16	.00	--	.06	30,000 *
17	.00	--	.04	30,000 *
18	.00	--	.05	30,000 *
19	.00	--	.06	30,000 *
20	.00	--	.05	30,000 *
21	.00	--	.04	30,000 *
22	.00	--	.03	30,000 *
23	.00	--	.04	30,000 *
24	.00	--	.05	30,000 *
25	.00	--	.06	30,000 *
26	.00	--	.06	30,000 *
27	.00	--	.06	30,000 *
28	.00	--	.05	30,000 *
29	.00	--	.06	30,000 *
30	.00	--	.06	30,000 *
TOT	0.00	--	1.59	NA

Grass Lysimeter Site

Instrumentation was located at the grass lysimeter site to compare Bowen-ratio estimated ET with ET based on data from weighing lysimeters (table 3). The ET estimates made with the Bowen-ratio method did not compare well with ET estimates made with the weighing-lysimeter data. The Bowen-ratio method estimated only about 41 percent of the ET that the weighing lysimeters measured for April 2 to May 13, 1991. The only days on which ET estimated with the Bowen-ratio agreed within 70 percent of the ET measured by the weighing-lysimeters were April 4, 9, 24, and 27 and May 4, 5, 6, and 7. Rain fell on or just before most of these days. Precipitation measured by the tipping-bucket rain gage and precipitation calculated from the weighing-lysimeter data agreed within 9.5 percent (table 3). In these comparisons, the weighing lysimeters were assumed to be the ET standard of accuracy and data from them to represent true conditions at the grass lysimeter site.

Figure 26 shows Bowen-ratio ET and weighing-lysimeter ET at the grass lysimeter site and Penman- Monteith ET at the Snively Basin site, all from April 5 to 22, 1991. Snively Basin ET is shown on figure 26 to compare ET from a full-cover grass site with ET from a sparse-canopy grass site.

For April 5-22, 1991, at the Snively Basin site, the Bowen-ratio ET closely matched the weighing-lysimeter ET for most of the morning hours on many days, then dropped off while the lysimeter ET continued at the same or greater rate than in the morning. This puzzling phenomenon may have been due to several causes: (1) instrument errors in measuring net radiation, soil-heat flux, air temperature, or vapor pressure; (2) vapor-pressure differences smaller than the 0.01 kilopascal resolution of the DEW-10 hygrometer; (3) leaks in the DEW-10 instrument, which would have reduced the vapor-pressure difference; (4) invalidation of assumptions in the Bowen-ratio method because of inadequate fetch (which may have resulted in advection of air from nearby unrepresentative areas) or non-uniform fetch (which may have resulted in uneven distribution of sources and sinks for sensible and latent-heat fluxes); or (5) conditions in the weighing lysimeters not representing conditions in the larger area surrounding the site.

Table 3.--*Precipitation and evapotranspiration at the grass lysimeter site, April 2 to May 13, 1991*

[PRC, precipitation; PRW, average precipitation measured by two weighing lysimeters; WL, average ET measured by two weighing lysimeters; BR, ET calculated with the Bowen-ratio method; mm, millimeter; TOT, monthly totals of daily precipitation and evapotranspiration; --, daily value not calculated]

	April				May			
Day	PRC (mm)	PRW (mm)	WL (mm)	BR (mm)	PRC (mm)	PRW (mm)	WL (mm)	BR (mm)
1	--	--	--	--	0.00	0.16	.49	.30
2	0.25	0.22	1.10	0.68	.00	.00	.60	.22
3	.25	.43	.70	.31	.00	.00	.44	.13
4	6.10	6.13	1.60	1.32	.00	.00	.39	.30
5	.00	.00	2.66	1.15	.00	.18	.43	.31
6	.00	.00	1.35	.41	.00	.00	.27	.24
7	.00	.00	1.03	.55	1.78	1.80	.37	.31
8	2.03	2.39	.86	.20	2.54	3.14	2.35	1.11
9	.25	.28	1.90	1.41	.00	.00	.78	.32
10	.00	.00	1.15	.42	.00	.09	.68	.16
11	.00	.00	1.43	.24	.00	.14	.54	.36
12	.00	.00	1.32	.23	.25	.36	.67	.44
13	.00	.00	1.15	.33	.00	.00	.43	.17
14	.25	.53	.92	.32				
15	5.33	5.17	1.00	.45				
16	.00	.00	2.10	.54				
17	.00	.00	1.50	.30				
18	.00	.00	1.46	.30				
19	.00	.00	1.25	.54				
20	.00	.00	1.21	.33				
21	.00	.00	1.16	.44				
22	.00	.00	1.04	.21				
23	.00	.00	.69	.29				
24	.00	.00	.58	.48				
25	.00	.00	.47	.25				
26	.00	.00	.65	.27				
27	.00	.00	.46	.39				
28	.00	.00	.48	.12				
29	.00	.00	.58	.26				
30	.00	.00	.57	.22				
TOT	14.46	15.15	32.37	12.96	4.57	5.87	8.44	4.37

Weighing-lysimeter data show that significant ET can occur at night (fig. 26). On April 5, 6, 9, 14, and 15, the lysimeter data show nighttime ET rates as high as 3 millimeters per day. These periods coincided with wind speeds between 7 and 14 meters per second; the ET may have its energy source from soil-heat flux or from sensible-heat flux transported by wind to the site from surrounding areas and vertical mixing of the airstream. The grass lysimeter site did not have much Bowen-ratio ET during the night. The Penman-Monteith method indicates there is ET at the Snively Basin site during the night, although somewhat less than the ET based on data from weighing lysimeters at the nearby grass lysimeter site (fig. 26). Most of this ET probably represented evaporation as plants generally stop transpiring after sundown (though when plants are at peak growth, some ET may occur for a few hours after sundown; see figures 21 and 22).

ET at the Snively Basin site significantly exceeded ET at the grass lysimeter site on all days except April 4, 5, and 9 (fig. 26). On these days, weighing-lysimeter ET and Snively Basin ET agreed within 75 percent. Because rain fell during part of these 3 days, the ET at both sites probably resulted primarily from soil evaporation and not plant transpiration so ET was similar at the two locations. On the other days, extra transpiration from the full-cover grasses at the Snively Basin site made up the difference.

Grasses at the Snively Basin site transpired at high rates through late April and early May (fig. 26; table 2), whereas the ET decreased at the grass lysimeter site (table 3), corresponding with observed plant senescence. The Snively Basin site, only 5 kilometers from the grass lysimeter site, lies more than 200 meters higher and receives 17 percent more annual precipitation than the grass lysimeter site (Stone and others, 1983).

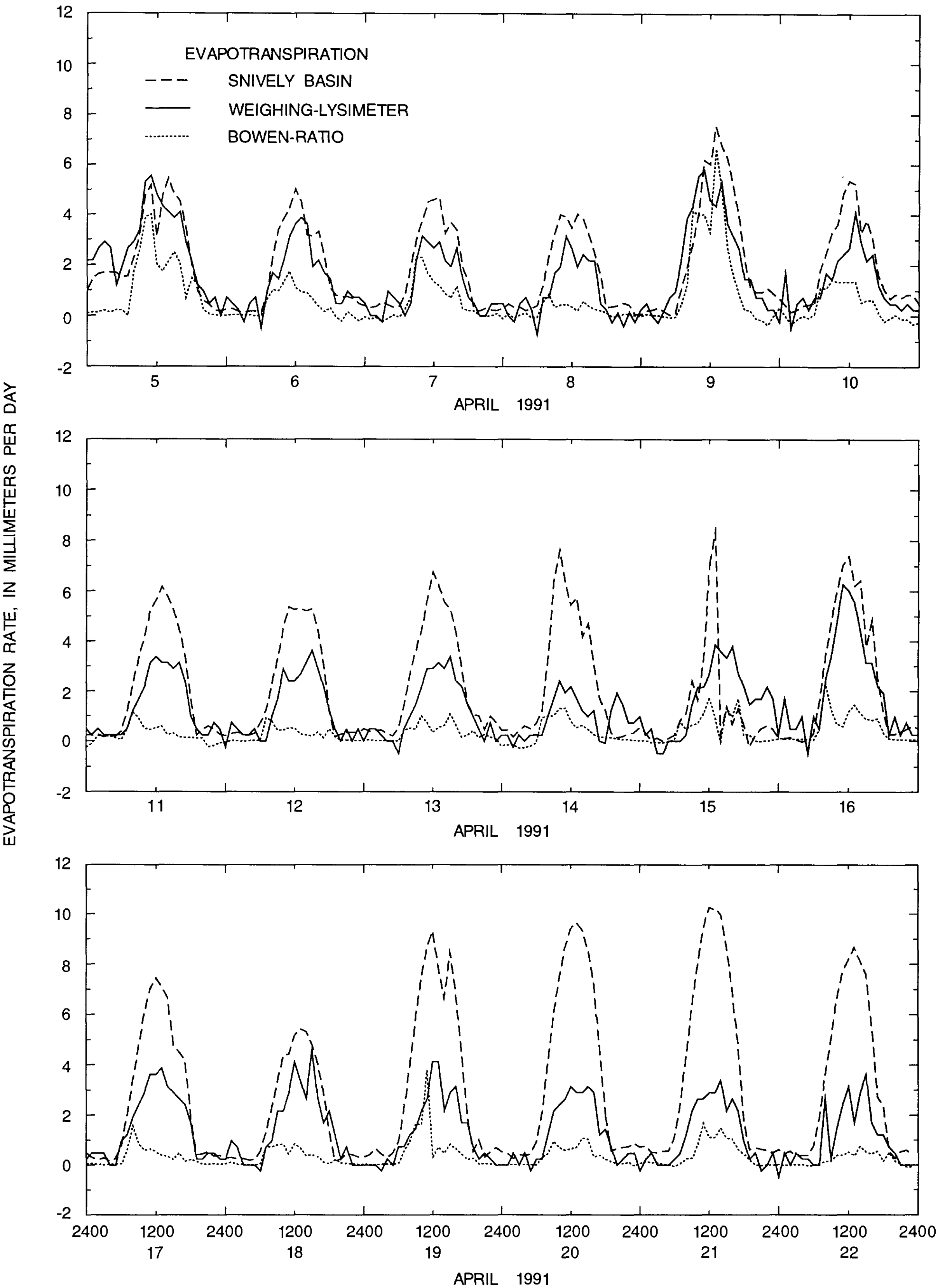

Figure 26.--Evapotranspiration rates at the Snively Basin and the grass lysimeter sites, April 5-22, 1991.

Turnbull National Wildlife Refuge Meadow Site

Latent-heat fluxes derived from the Bowen-ratio method were used to calibrate the Penman-Monteith equation for canopy resistances at the Turnbull meadow site. Daily-average canopy resistances were determined to recalculate the latent-heat fluxes and ET with the Penman-Monteith method for the entire period of study (table 4; fig. 27).

At the Turnbull meadow site, significant ET probably began on warm days in March and April; this was missed because data was not collected until May 15, 1991. In mid-May, daily ET ranged from just less than 1 millimeter to 3 millimeters. Daily ET gradually rose through late May and reached a peak in June when it ranged from 2 to 5 millimeters. Canopy resistances in May and June averaged nearly 100 seconds per meter, approaching potential ET conditions. The frequent, and sometimes heavy, precipitation during this period probably was responsible for this. In July, daily ET ranged from 1 to 4 millimeters as the meadow vegetation matured. Canopy resistances also began to rise somewhat, ranging from 100 to more than 1,000 seconds per meter. During August, daily ET began to drop from 2 to less than 1 millimeter as plants began to senesce. Canopy resistances ranged from about 500 to more than 3,000 seconds per meter, except during and shortly after rainfall, when the canopy resistance would decrease to about 100 seconds per meter (August 6, 1991, in table 4, for example). In September, as the dried soils and the vegetation perished, daily ET was generally less than 0.6 millimeter. Canopy resistances ranged from 2,000 to 7,000 seconds per meter, again except during and shortly after periods of rainfall (September 8, 1991, in table 4, for example).

Turnbull National Wildlife Refuge Marsh Site

Data to calculate ET with the Penman and Penman-Monteith methods were collected from May 15 to September 30, 1991. Despite some differences between the Turnbull marsh and Turnbull meadow sites, a detailed comparison of net radiation, soil-heat flux, relative humidity, and air temperature for 30 days (6 days each in May, June, July, August, and September) at both sites indicated that these measurements compared closely (fig. 28). Net radiation varied 6.5 percent, soil-heat flux varied 6.6 percent, air temperature varied 2.1 percent, and relative humidity varied 1.3 percent. The range of these parameters is within or close to the range of instrument error at the Snively Basin site. Wind speed, however, was 25.5 percent lower at the Turnbull marsh site than at the Turnbull meadow site. The lower wind speeds at the Turnbull marsh site might be explained by (1) the shorter canopy and lower altitude of the marsh site compared with the meadow site (wind speeds decrease with decreasing altitude in a profile); (2) trees being closer to the marsh site than to the meadow site, which would produce a windbreak effect; or (3) instrument error.

Because of the close comparisons of most data and plant species at the two sites, the soil-moisture canopy resistance correlation developed for the Turnbull meadow site was applied to the Turnbull marsh site. ET was then estimated with the Penman-Monteith method for the Turnbull marsh site using this correlation and soil-moisture data collected at the marsh site.

For May 15 to September 30, 1991, at the Turnbull marsh site, Penman-Monteith ET was 65 percent greater than Penman-Monteith ET for the Turnbull meadow site (table 5). Marsh site soils had an average of twice the water content of meadow site soils (fig. 29), which during May and June resulted in daily canopy resistances that were less than 100 seconds per meter. This, in turn, allowed actual ET to be more than 70 percent of the potential ET during May and June (table 5). Higher rainfall at the Turnbull marsh site, compared with the Turnbull meadow site, also contributed to lower canopy resistances and higher actual ET at the Turnbull marsh site; during May 15 to September 30, 1991, the Turnbull marsh site received 20 percent more precipitation than the Turnbull meadow site. Sixty-four percent of this extra rainfall was due to a thunderstorm on June 28, which produced nearly 16 millimeters of rainfall at the Turnbull marsh site but none at the Turnbull meadow site.

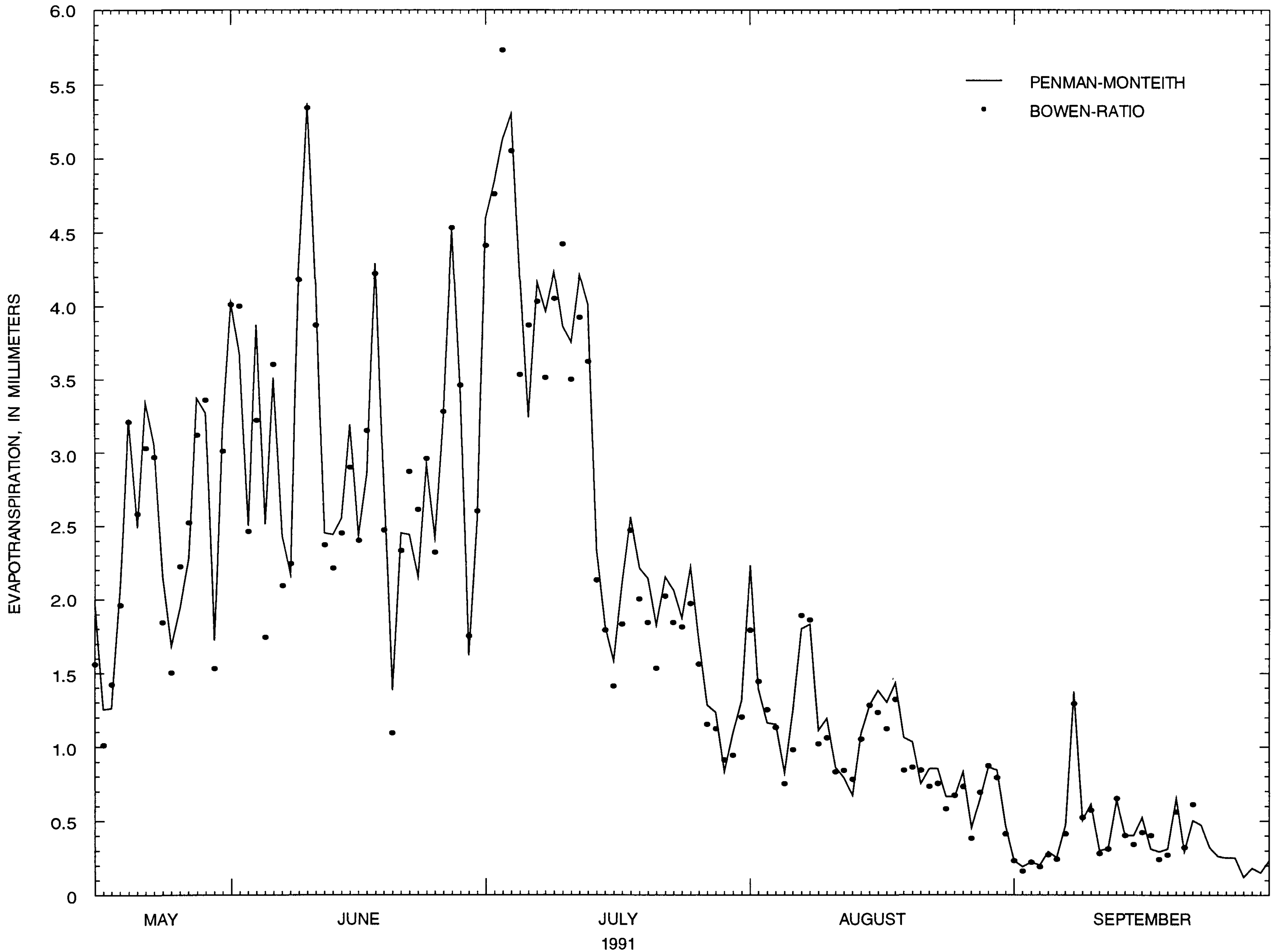

Figure 27.--Evapotranspiration estimated with the Bowen-ratio and Penman-Monteith methods for the Tumbull meadow site, May 16 to September 30, 1991.

Table 4.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Turnbull meadow site, May 16 to September 30, 1991*

[PRC, precipitation; BR, evapotranspiration, Bowen-ratio method; PM, evapotranspiration, Penman-Monteith method; RC, canopy resistance; TOT, monthly totals of daily precipitation and evapotranspiration; TR, data suggest trace of precipitation; mm, millimeter; s/m, seconds per meter; NA, not applicable; *, partly estimated or estimated; --, daily or monthly value not calculated]

	May 1991				June 1991				July 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	--	--	--	--	0.00	4.01	4.02	109	0.00	4.41*	4.59	109
2	--	--	--	--	.00	4.00	3.67	158	.00	4.76*	4.84	141
3	--	--	--	--	.00	2.46	2.50	185	.00	5.73*	5.13	168
4	--	--	--	--	.00	3.22	3.87	120	.00	5.05*	5.30	191
5	--	--	--	--	.25	1.74	2.51	80.2	.00	3.53*	4.20	231
6	--	--	--	--	5.08	3.60	3.51	63.8	.00	3.87*	3.24	266
7	--	--	--	--	6.60	2.09	2.43	35.9	.00	4.03*	4.16	180
8	--	--	--	--	.00	2.24	2.17	73.4	.00	3.51*	3.96	249
9	--	--	--	--	.00	4.18	4.26	61.8	.25	4.05*	4.23	189
10	--	--	--	--	.00	5.34	5.37	85.2	.00	4.42*	3.86	190
11	--	--	--	--	1.02	3.87	4.15	106	.00	3.50	3.75	262
12	--	--	--	--	.00	2.37	2.45	121	.00	3.92	4.21	302
13	--	--	--	--	.25	2.21	2.44	93.7	1.52	3.62	4.01	268
14	--	--	--	--	.00	2.45	2.55	119	.00	2.13	2.33	262
15	--	--	--	--	.00	2.90	3.19	126	.00	1.79	1.82	440
16	0.76	1.56	1.96	80.6	.00	2.40	2.43	135	.51	1.41	1.58	127
17	10.16	1.01	1.25	85.0	.00	3.15	2.86	131	1.78	1.83	2.12	105
18	.00	1.42	1.26	40.2	.00	4.22	4.29	103	.00	2.47	2.56	271
19	.00	1.96	2.07	68.2	3.56	2.47	2.82	78.2	.00	2.00	2.21	417
20	.00	3.21	3.25	130	1.27	1.09	1.38	24.9	.00	1.84	2.14	512
21	.00	2.58	2.49	97.8	.51	2.33	2.45	45.8	.00	1.53	1.82	625
22	.00	3.03	3.34	107	.00	2.87	2.44	111	.00	2.02	2.15	633
23	.00	2.97	3.06	131	.00	2.61	2.15	208	.00	1.84	2.06	818
24	.00	1.84	2.15	120	4.32	2.96	2.92	76.0	.25	1.81	1.87	875
25	.51	1.50	1.68	133	.25	2.32	2.42	74.8	3.81	1.97	2.22	178
26	.00	2.22	1.94	147	.00	3.28	3.23	113	.00	1.56	1.72	521
27	1.52	2.62	2.28	121	.00	4.53	4.52	113	.00	1.15	1.28	871
28	.00	3.12	3.37	92.0	.00	3.46	3.43	125	.00	1.12	1.23	1,050
29	.00	3.36	3.27	98.9	15.24	1.75	1.62	52.5	.00	.91	.83	1,660
30	1.52	1.53	1.72	59.1	.00	2.60	2.54	114	.00	.94	1.09	1,200
31	.00	3.01	3.16	105					.00	1.20	1.31	1,430
TOT	13.96	36.84	38.23	NA	38.35	88.72	90.59	NA	8.12	83.92	87.82	NA

Table 4.--*Daily and monthly precipitation, evapotranspiration, and canopy resistance at the Turnbull meadow site, May 16 to September 30, 1991*

	August 1991				September 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)	PRC (mm)	BR (mm)	PM (mm)	RC (s/m)
1	1.78	1.79	2.23	467	0.00	0.23	0.23	3,530
2	.00	1.44	1.39	906	.00	.16*	.19	5,470
3	.00	1.25	1.16	1,480	.00	.22*	.22	5,400
4	.00	1.13	1.15	1,640	.00	.19*	.20	7,240
5	TR	.75	.82	504	.00	.27*	.29	5,530
6	9.40	.98	1.24	1,120	.00	.24*	.25	6,520
7	TR	1.89	1.80	473	.00	.41	.47	1,690
8	.00	1.86	1.83	771	7.11	1.29*	1.37	185
9	.00	1.02	1.11	1,170	.00	.52*	.50	1,190
10	TR	1.06	1.19	490	.00	.57*	.61	1,590
11	.00	.83	.86	1,150	.00	.28*	.30	3,560
12	.76	.84	.79	1,250	.00	.31*	.31	3,740
13	.00	.78	.67	1,280	TR	.65	.64	1,090
14	.00	1.05	1.09	762	.00	.40*	.40	2,050
15	.00	1.28	1.28	964	.00	.34*	.40	2,470
16	.00	1.23	1.38	1,060	.00	.42*	.52	2,310
17	.00	1.12	1.30	1,240	.00	.40*	.31	2,900
18	.00	1.32	1.43	1,270	.00	.24*	.29	3,300
19	.00	.84	1.06	1,530	.00	.27*	.31	3,990
20	.00	.86	1.03	1,670	.00	.56*	.65	1,400
21	.00	.84	.75	2,580	.00	.32*	.29	2,480
22	.00	.73	.85	2,070	.00	.61*	.50	1,440
23	.00	.75	.85	1,500	.00	--	.47	1,930
24	.00	.58	.66	2,000	.00	--	.32	3,240
25	.00	.67	.66	1,420	.00	--	.26	4,040 *
26	.00	.73	.83	1,490	.00	--	.25	4,840 *
27	.00	.38*	.45	2,160	.00	--	.25	5,100 *
28	TR	.69	.64	794	.00	--	.12	6,960
29	.00	.87	.86	1,270	.00	--	.18	5,700
30	.00	.79	.84	1,870	.00	--	.15	7,490
31	.00	.41*	.46	2,880				
TOT	12.19	30.76	32.66	NA	7.11	--	11.25	NA

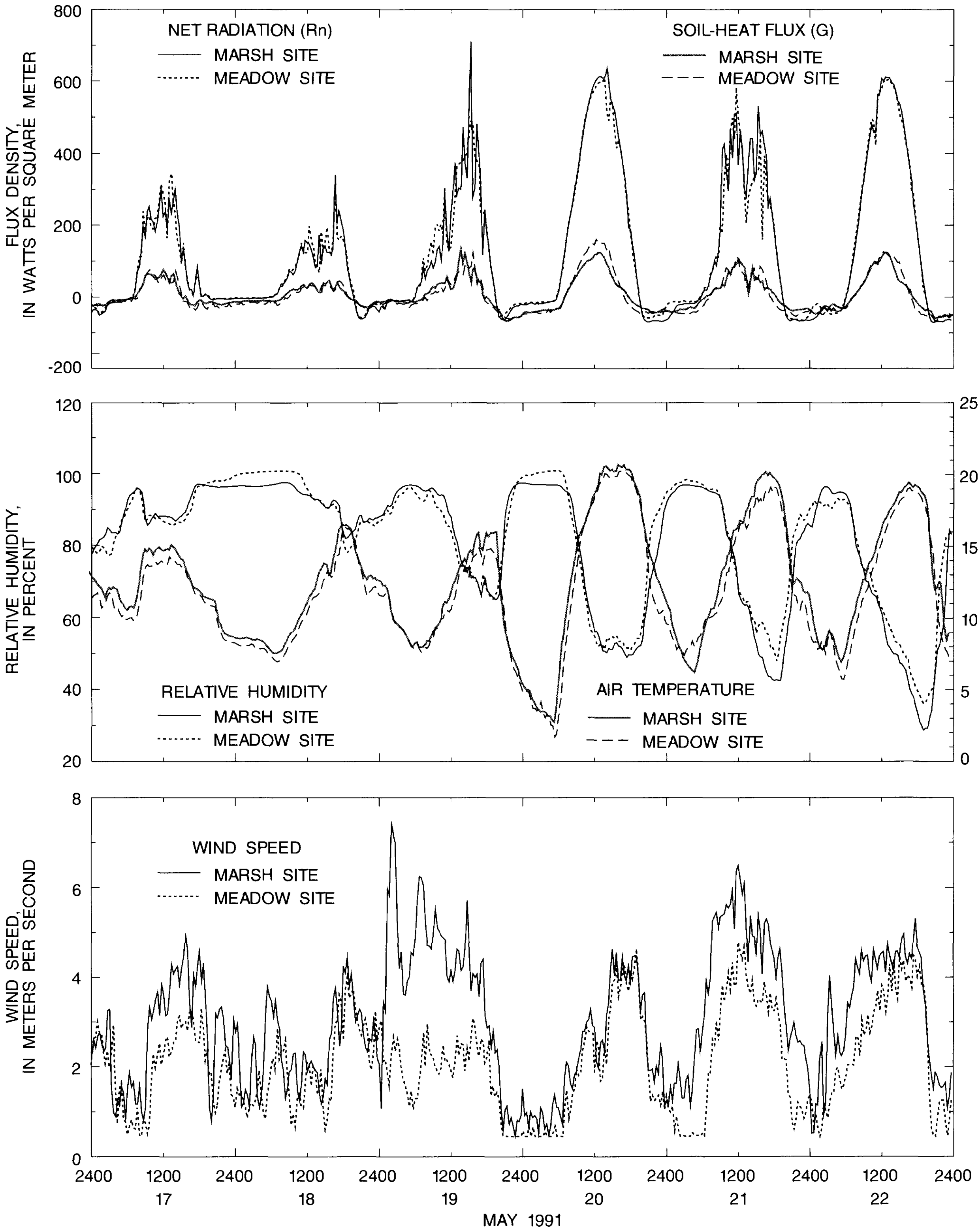

Figure 28.--Net radiation, soil-heat flux, relative humidity, air temperature, and wind speed at the Turnbull meadow and marsh sites, May 17-22, 1991 and June 7-12, 1991

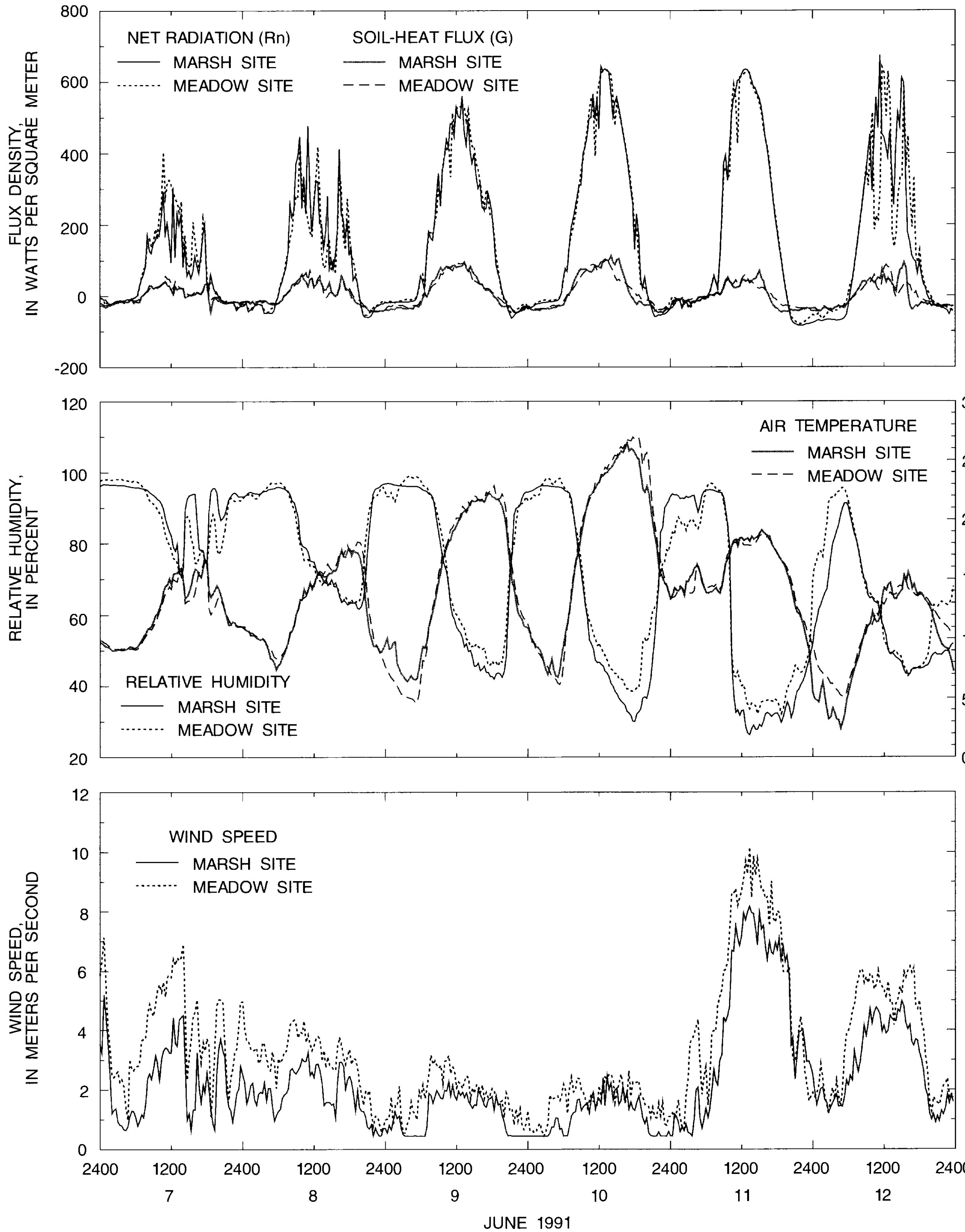

Figure 28.--Continued

Table 5.--*Daily and monthly precipitation, potential and actual evapotranspiration, and canopy resistance at the Turnbull marsh site, May 16 to September 30, 1991*

[PRC, precipitation; PO, potential evapotranspiration; PM, evapotranspiration, Penman-Monteith method; RC, canopy resistance; TOT, monthly totals of daily precipitation and evapotranspiration; mm, millimeter; s/m, seconds per meter; NA, not applicable; --, daily or monthly value not calculated]

	May 1991				June 1991				July 1991			
Day	PRC (mm)	PO (mm)	PM (mm)	RC (s/m)	PRC (mm)	PO (mm)	PM (mm)	RC (s/m)	PRC (mm)	PO (mm)	PM (mm)	RC (s/m)
1	--	--	--	--	0.00	6.73	5.24	46.4	0.00	6.35	5.69	26.7
2	--	--	--	--	.00	9.55	6.72	48.3	.00	7.14	6.39	34.8
3	--	--	--	--	.00	10.03	5.82	50.2	.00	8.21	7.21	40.8
4	--	--	--	--	.00	6.65	4.77	53.2	.00	11.73	8.73	49.4
5	--	--	--	--	.51	4.03	3.31	25.5	.00	12.07	7.70	64.7
6	--	--	--	--	4.06	4.49	3.70	28.1	.00	9.09	5.90	67.5
7	--	--	--	--	8.89	2.23	1.82	26.7	.00	7.58	5.25	82.6
8	--	--	--	--	.00	3.39	2.67	36.0	.00	7.52	5.65	91.7
9	--	--	--	--	.00	5.24	4.37	44.4	.00	7.31	5.09	97.9
10	--	--	--	--	.00	7.01	5.84	53.6	.00	8.22	4.86	108
11	--	--	--	--	.76	13.18	6.23	58.0	.00	8.03	5.30	110
12	--	--	--	--	.00	6.67	3.56	67.0	.00	8.08	5.92	113
13	--	--	--	--	.00	5.13	2.71	69.1	1.27	10.20	7.00	65.1
14	--	--	--	--	.00	6.28	3.31	71.7	.00	5.56	3.98	77.2
15	--	--	--	--	.00	6.09	3.87	71.8	.00	6.76	4.18	89.3
16	0.76	2.93	2.17	32.9	.25	7.46	3.77	72.1	.51	2.21	1.40	85.1
17	13.72	2.02	1.74	26.4	.00	5.30	3.29	77.5	2.54	3.72	2.33	81.4
18	.00	1.64	1.35	28.7	.00	6.96	4.44	77.5	.00	7.08	4.45	91.2
19	4.32	3.15	2.61	27.2	2.79	3.97	2.94	35.1	.00	8.13	4.64	110
20	.00	6.93	5.57	29.9	1.02	1.47	1.08	39.5	.00	9.00	4.70	141
21	.00	5.76	4.17	36.8	.25	2.59	2.11	42.7	.00	8.03	3.64	189
22	.00	7.55	5.27	40.4	.00	3.77	3.02	45.3	.00	9.69	4.22	212
23	.00	6.37	4.72	43.7	.00	5.03	4.02	48.1	.00	10.03	4.51	251
24	.00	4.65	2.95	46.6	1.27	2.87	2.45	37.5	.25	8.97	4.12	280
25	.51	4.80	2.87	46.4	5.33	4.00	3.09	34.4	6.35	4.39	2.43	156
26	.00	4.47	3.20	50.2	.00	5.53	4.45	39.0	.00	7.71	2.80	262
27	.00	4.80	3.43	51.6	.00	6.26	5.20	43.1	.00	8.78	2.91	293
28	.00	5.61	4.03	52.8	15.75	4.84	4.02	47.0	.00	8.88	2.99	317
29	.25	6.18	4.39	49.4	20.57	2.34	2.04	26.1	.00	11.07	3.21	331
30	1.27	2.57	1.77	43.1	.00	4.65	3.81	26.7	.00	8.87	2.93	345
31	.00	6.00	4.40	44.7					.00	8.57	3.78	362
TOT	20.57	75.43	54.64	NA	61.45	163.74	113.67	NA	10.92	248.98	143.91	NA

Table 5.--*Daily and monthly precipitation, potential and actual evapotranspiration, and canopy resistance at the marsh site, May 16 to September 30, 1991*

	August 1991				September 1991			
Day	PRC (mm)	PO (mm)	PM (mm)	RC (s/m)	PRC (mm)	PO (mm)	PM (mm)	RC (s/m)
1	0.51	7.33	3.36	210	0.00	7.67	0.93	842
2	.00	8.13	3.72	251	.00	6.12	1.00	877
3	.00	8.72	4.00	274	.00	7.10	1.15	917
4	.00	8.22	3.82	307	.00	6.66	1.34	936
5	.00	3.02	.96	347	.00	6.29	1.43	961
6	1.27	6.40	2.73	362	.00	7.65	1.41	986
7	.00	5.64	3.13	190	.00	7.28	.73	1,010
8	.00	8.96	4.40	215	2.03	1.99	.68	175
9	.00	9.89	3.92	236	.00	6.21	2.14	202
10	.00	5.70	2.00	264	.00	5.38	2.51	234
11	.00	6.44	2.48	295	.00	5.14	2.28	288
12	2.79	6.10	3.39	169	.00	6.91	2.48	318
13	.00	5.12	2.15	242	.00	8.08	1.53	344
14	.00	5.04	2.14	294	.00	5.30	1.67	372
15	.00	7.22	2.92	314	.00	5.14	1.75	414
16	.00	6.71	3.09	340	.00	6.01	1.93	451
17	.00	7.63	3.39	388	.00	8.19	1.55	492
18	.00	6.64	2.82	442	.00	5.97	1.56	522
19	.00	8.99	2.68	475	.00	6.30	1.70	554
20	.00	9.04	2.41	529	.00	8.42	1.33	589
21	.00	9.26	2.41	590	.00	6.78	.96	627
22	.00	8.46	2.23	618	.00	4.44	.94	661
23	.00	10.28	1.55	668	.00	5.10	1.04	697
24	.00	7.43	1.51	700	.00	4.56	1.17	705
25	.00	7.36	1.13	730	.00	5.07	1.21	736
26	.00	6.76	1.42	789	.00	4.92	1.30	744
27	.00	6.24	1.03	857	.00	5.09	1.36	769
28	.51	5.83	.85	585	.00	4.64	.99	769
29	.25	7.31	1.56	653	.00	4.44	1.13	769
30	.00	7.42	1.81	781	.00	6.15	1.20	796
31	.00	8.01	1.43	810				
TOT	5.33	225.30	76.44	NA	2.03	179.00	42.40	NA

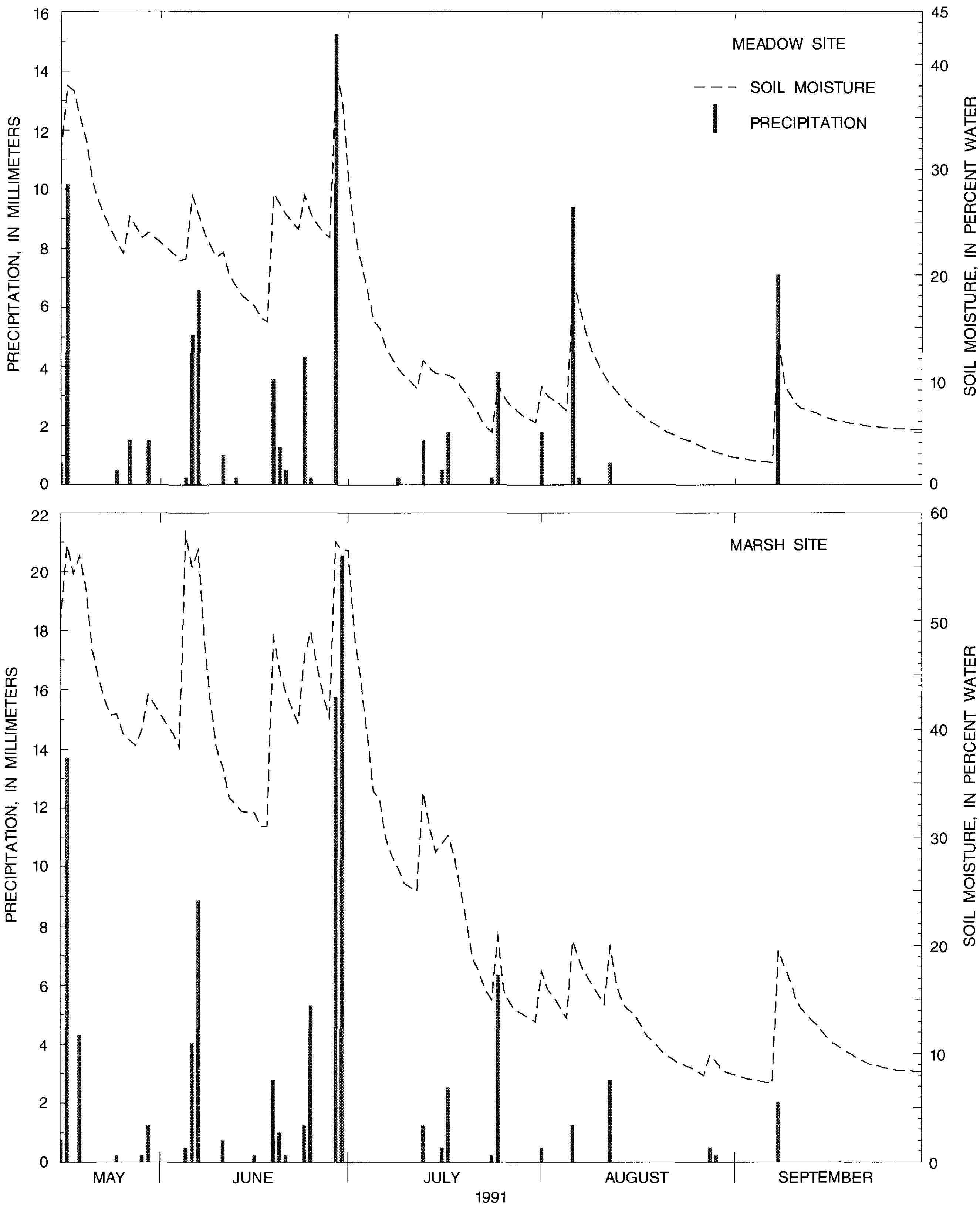

Figure 29.--Precipitation and soil moisture for May 16 to September 30, 1991 at the Tumbull meadow and marsh sites.

Environmental Influences

The Bowen-ratio method could be used to estimate ET for only parts of the study period. Most net radiation, soil-heat flux, soil temperature, soil moisture, and air temperature data were of good quality and only a few problems occurred in making those measurements. Accurate vapor-pressure data were much more difficult to obtain, however.

Generally, when air temperatures were above freezing and vegetation was actively growing, excellent vapor-pressure data were collected. At other times, instrument problems (from freezing weather, low humidity, high wind speeds, air leaks in the DEW-10 system, and possible advection of air from areas different than the site) resulted in inaccurate vapor-pressure measurements. Air temperatures or dew points below freezing caused ice to form on the mirror of the cooled-mirror hygrometer and produced erroneous vapor-pressure measurements. Dry soil and air sometimes produced a lot of noise in the vapor-pressure data and made such data difficult to interpret. High wind speeds during periods of small vapor-pressure gradients reduced vapor-pressure gradients below the ability of the DEW-10 instrument to accurately measure them. Air leaks in the DEW-10 system also might have reduced the vapor-pressure gradient. However, no leaks were found by visual inspection, although pressurization testing of the whole system to discover pinhole-sized leaks was not done. Difficulties in obtaining accurate vapor-pressure data were also encountered at the Turnbull meadow site during late summer and early fall, but not as severe as what was encountered at the ALE sites.

On many days during mid summer and fall at the Snively Basin site, instrument error or advection of moist air may have reversed the vapor-pressure gradient such that vapor pressure increased with height. These reversed vapor-pressure gradients were recorded over full canopies at the Snively Basin and Turnbull meadow sites (when plants were senescing and becoming dry and brittle) and at the grass lysimeter site nearly anytime except during and shortly after rainfall. ET calculated with the Bowen-ratio and Penman-Monteith methods at the Snively Basin site and ET calculated from weighing-lysimeter data at the grass lysimeter site were compared for August 20-28, 1990 (fig. 30). On August 20, conditions at the sites were dry—soil moisture was estimated to be about 2.4 percent and ET was only about 0.2 millimeter for the day. On August 21, thunderstorms produced 28.19 millimeters of rainfall at Snively Basin and 20.06 millimeters at the grass lysimeter site. Bowen-ratio and Penman-Monteith ET compared closely with ET based on data from the weighing lysimeters on August 21, a day with cloudy, wet conditions throughout the daytime.

However, on August 22, when sunshine and clearer skies allowed for the expected evaporation, which was confirmed by the weighing lysimeters (fig. 30), Bowen-ratio ET climbed through mid-morning, then reversed direction and plummeted. The DEW-10 data indicated a reversal in the vapor-pressure gradient, with positive temperature gradients, which led to negative ET rates by the Bowen-ratio method. During late afternoon the vapor-pressure gradient reversed again, resulting in ET rates comparable to those shown by the weighing lysimeters. This situation occurred on every day after the 22nd as well (fig. 30). By using only those periods where the vapor-pressure gradient data were believed to be accurate, reasonable estimations of ET were made with the Penman-Monteith method, compared with the weighing-lysimeter measured ET.

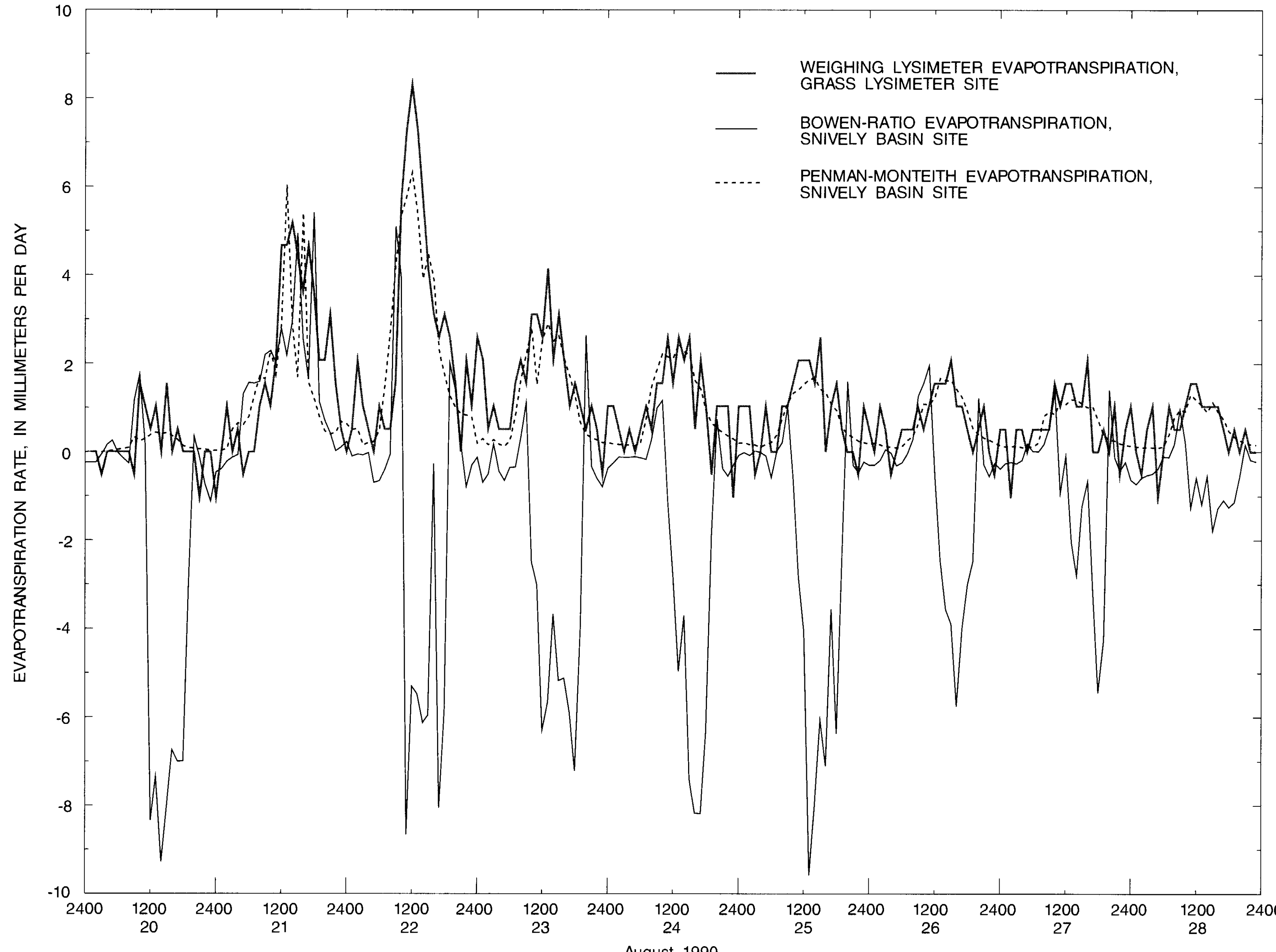

Figure 30.--Rates of Bowen-ratio and Penman-Monteith estimated evapotranspiration at the Snively Basin site and weighing-lysimeter evapotranspiration at the grass lysimeter site, August 20-28, 1990.

Water Budget for the Snively Basin Site

Long-term ET estimates are important to water-resources managers because ET data, combined with precipitation and surface-runoff data, allows them to make estimates of recharge to subsurface systems: the soil profile, the unsaturated zone, and ground water. Estimates of precipitation, ET, and surface runoff are required to calculate a water budget. The remainder is deep percolation and the change in soil moisture.

Data collected at the Snively Basin site were used to calculate a water budget for August 20, 1990, to September 30, 1991. During that period, water-storage changes and ET were near zero because plants were dead or dormant for the season and upper-layer soil moisture was about 2.5 percent.

A tipping-bucket rain gage measured precipitation at the Snively Basin site for the entire period of study. The gage worked well except during freezing weather when the tipping mechanism stuck because of ice and because snow did not penetrate below the screen of the collection funnel. When temperatures rose above freezing, however, the collected snow and ice melted and was recorded. The tipping-bucket gage measured only about half the precipitation that fell as snow, compared with precipitation data collected by a storage gage about 30 meters from the Snively Basin site. Precipitation data for the winter were supplemented by data from this storage gage to provide a more accurate assessment of precipitation amounts and timing. Also, the gage may not have measured precipitation accurately during high winds because the gage was not shielded (Linsley and others, 1982). Dewfall and trace precipitation were not measured at the Snively Basin site. Dewfall is estimated to compose less than 5 percent of the precipitation on the ALE Reserve (Rickard and others, 1988). To account for unmeasured trace precipitation, dew fall, and wind effects on the tipping bucket gage, the measured precipitation was increased by 5 percent. The precipitation measured at the Snively basin site from August 20, 1990, to September 30, 1991, totaled 248 millimeters. With the 5 percent adjustment, the total estimated precipitation was 260 millimeters.

Surface runoff was estimated to be zero for the period of study. Only two storms exceeded 20 millimeters of precipitation (August 21, 1990, and June 20, 1991, on table 2) and the overland runoff at the Snively Basin site was estimated to be low because the soils were relatively dry and were probably able to absorb the rainfall. Therefore, for the water budget at the Snively Basin site, only precipitation and ET were considered; the remainder of the water budget would be the change in recharge to subsurface systems.

On August 20, 1990, soil moisture at the Snively Basin site was 2.4 percent (fig. 31) and ET for the day was 0.1 millimeter. A steep slope in the cumulative ET plot after the August 21, 1990, rainfall was followed by a leveling-off period in September when ET was near zero. Rains from October to February (36 percent of the precipitation was received in this period, table 2) added moisture to the soil profile (fig. 32) whereas ET remained fairly low (fig. 31) because of low net radiation and low temperatures. Only 16 percent of the ET during the water-budget period occurred from October to February (table 2). From March to July, plants quickly used up the water stored in the soil profile and the slope of the cumulative ET plot steepened dramatically; 76 percent of the ET occurred during this period—April alone accounted for 25 percent. From August through September, the slope of the plot began to level out again as rainfall became uncommon and the soil moisture again approached 2.5 percent. The slope of the plot then became steeper for short periods only after major summer rainfalls. Figures 31 and 32 show that some rainfall from the August 21, 1990, storm was held in the profile until spring of 1991. The quantity of water stored in surface soil appears to be about 1.5 millimeters (fig. 32). The whole soil profile may have stored more than that, however, because some water from the August 21, 1990, storm would have drained below the top 0.2 meter (soil-moisture measurements were taken in the top 0.2 meter). Dead and dormant plants at the site in August did not transpire water and may have acted as a mulch to shade the soil surface, which would help slow evaporation

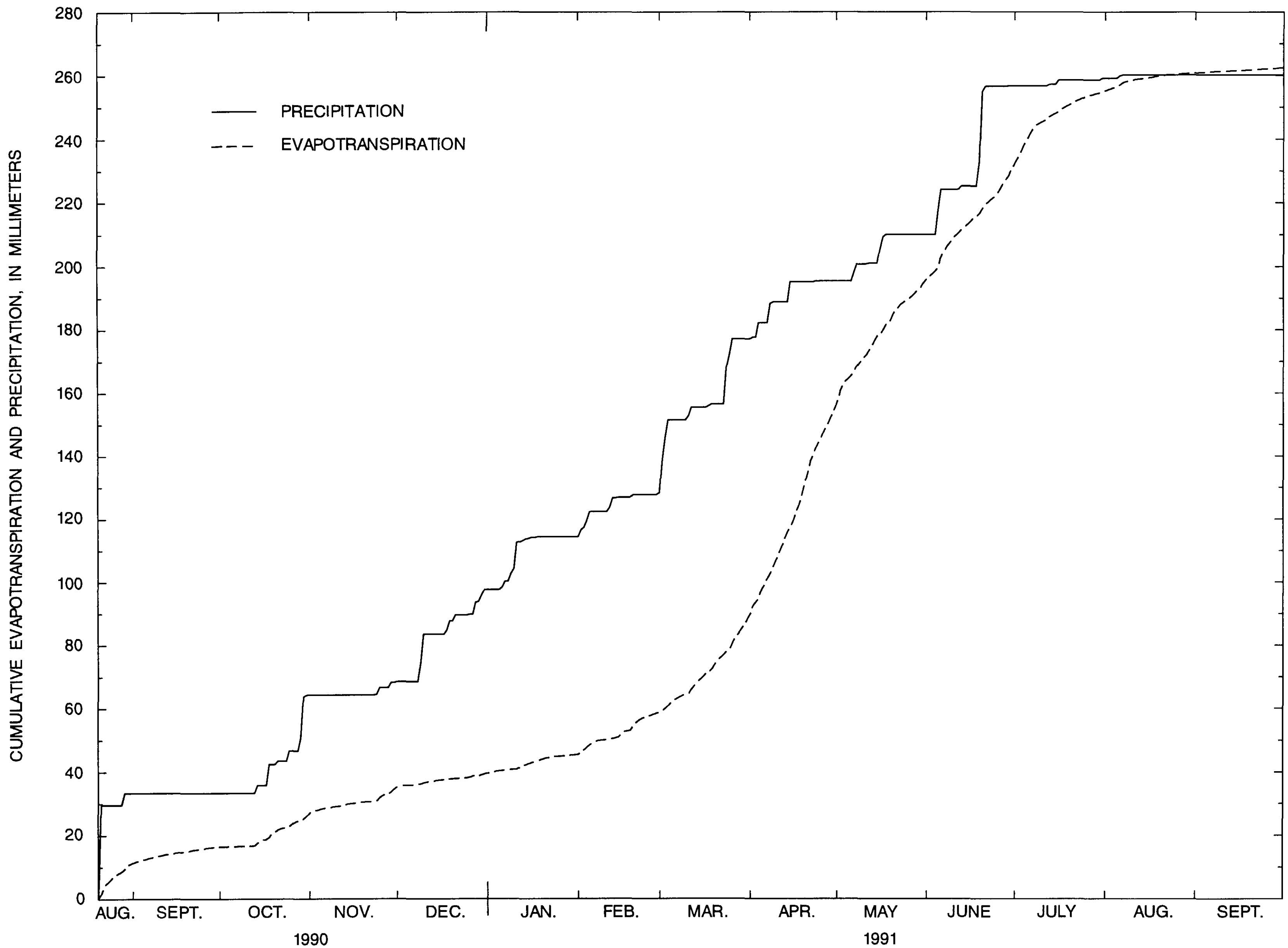

Figure 31.--Cumulative evapotranspiration and precipitation at Snively Basin site, August 21, 1990 to September 30, 1991.

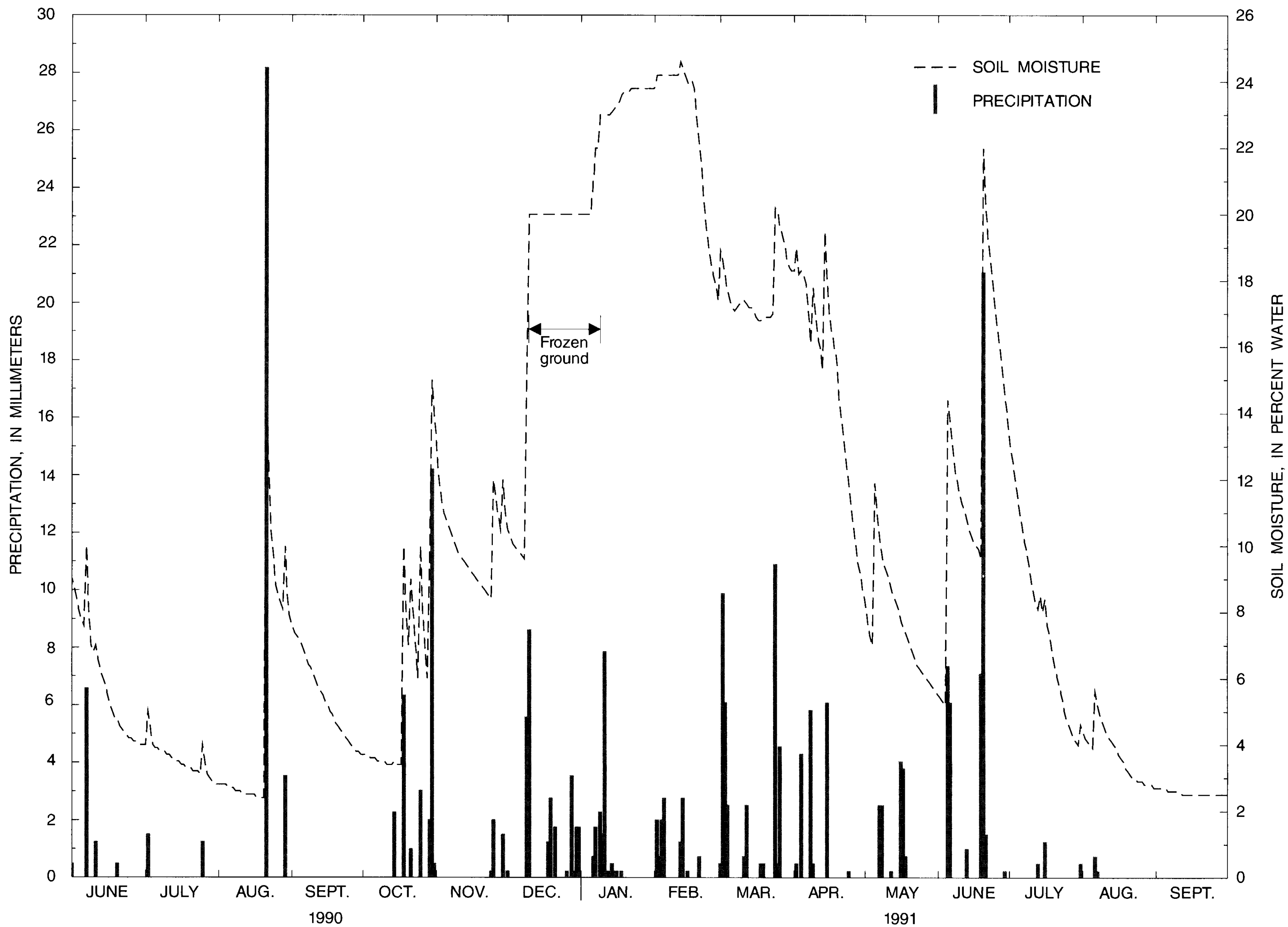

Figure 32.--Precipitation and soil moisture at the Snively Basin site, May 31, 1990 to September 30, 1991.

The Snively Basin site water budget indicated that all precipitation from August 20, 1990, through September 30, 1991, became ET. Total estimated precipitation was 260 millimeters and Penman-Monteith estimated ET was 262 millimeters. These figures indicate that 101 percent of the precipitation was returned to the atmosphere as ET; no water was available as recharge to subsurface systems.

If possible instrument errors are included in the water-budget formulation, a range of precipitation and ET estimates results. The error analysis on instruments indicated a worst-case error of ±12 percent in the ET estimates. Assuming this worst case, the estimated Penman-Monteith ET could be as low as 231 millimeters or as high as 293 millimeters. Also, actual precipitation might have been what was measured or as much as 10 percent higher, based on comparisons between precipitation measured with a tipping bucket rain gage and with weighing lysimeters. If the measured precipitation of 248 millimeters is increased by 10 percent, this gives 273 millimeters. A range of precipitation of 248 to 273 millimeters and a range of ET of 231 to 293 millimeters gives a worst-case ET-precipitation water budget range of 85 percent to 118 percent. With these figures, as much as 15 percent of the precipitation could go into subsurface system storage or 18 percent of the ET could be withdrawn from storage previously accumulated. The average of these ranges is 102 percent, still indicating that all precipitation was returned to the atmosphere as ET in the water budget period.

With or without possible instrument errors included, the water budget for August 20, 1990, to September 30, 1991, at the Snively Basin site suggests that little, if any, of the precipitation recharged ground water. For this period, at this site, it appears that the soil profile held most moisture that fell from late summer to early spring, then the moisture was consumed by plants and released from the profile through ET. Soil evaporation alone probably occurred from mid-summer through late winter as the plants perished or became dormant.

No water budget could be formulated for the grass lysimeter site or either of the Turnbull NWR sites because data to calculate ET were not collected for an entire year for those sites.

SUMMARY

Evapotranspiration (ET) was evaluated at four grasslands in eastern Washington. Two sites were located on the Arid Lands Ecology (ALE) Reserve in Benton County: one at a full-canopy grassland in Snively Basin, the other a sparse-canopy grassland adjacent to a pair of weighing lysimeters. Two sites were located on the Turnbull National Wildlife Refuge (NWR) in Spokane County: one at a full-canopy grassland in a meadow, the other a full-canopy grassland near a marsh.

The periods of study and methods used at the four sites varied. The periods of study were May 1990 to September 1991 for the Snively Basin site, April to May 1991 for the ALE Reserve sparse-canopy grassland site, and May 1991 to September 1991 for both sites on the Turnbull NWR. ET and energy-budget fluxes were calculated with the Bowen-ratio and Penman-Monteith methods for the Snively Basin site and the Turnbull NWR meadow site. For the sparse-canopy grass site, ET and energy-budget fluxes were calculated with the Bowen-ratio method; ET also was calculated from weighing-lysimeter data. The Penman and Penman-Monteith methods calculated potential and actual ET and energy-budget fluxes for the Turnbull marsh site.

The Bowen-ratio method could estimate ET for the Snively Basin site and Turnbull meadow site during the main part of the growing season, March to July. The Bowen-ratio method could not be used, however, during the remainder of the year at these two sites because of invalid vapor-pressure data caused by instrumentation problems, environmental conditions outside the limits of the instruments, or, possible advection of air from other areas. For the grass lysimeter site, the Bowen-ratio method estimated only 41 percent as much ET as estimated from the weighing-lysimeter data. This may have been due to invalid net radiation, air-temperature, or vapor-pressure data caused by instrumentation problems, possible advection of air from other areas or conditions in the lysimeters being unrepresentative of overall site conditions.

The Penman-Monteith method estimated ET for all periods of study at the Snively Basin, Turnbull meadow, and Turnbull marsh sites; the accuracy of the estimates could not be determined for those periods without accurate Bowen-ratio data with which to determine canopy resistance. The canopy resistance, as used in this report, represents an overall calibration factor between the Bowen-ratio and Penman-Monteith methods. Latent-heat fluxes calculated with the Bowen-ratio method were used in the Penman-Monteith equation to determine the canopy resistance at the Snively Basin and Turnbull meadow sites. The Penman-Monteith equation was then used to calculate ET for the entire periods of study at each of these sites. For periods lacking the data to calculate latent-heat fluxes with the Bowen-ratio method, the canopy resistance was estimated from resistances of previous or subsequent periods or based on site characteristics, such as soil moisture.

Canopy resistances for the Turnbull marsh site were estimated with soil-moisture data for the Turnbull marsh site, as well as with a soil-moisture canopy- resistance relation developed for the Turnbull meadow site. Most measured variables at the Turnbull meadow and Turnbull marsh site agreed within 7 percent of one another and vegetative cover at the two sites was similar. The Penman method was used to provide estimates of potential ET (canopy resistance equals zero) at the Turnbull marsh site.

Careful consideration of instrumentation, aerodynamic resistance to heat, and canopy resistance were required in the data analysis. Instrumentation inaccuracies in all measurements did not appear to be a major factor in the data quality or in calculation of the energy-budget fluxes or ET estimates. Overall, like types of instruments measuring net radiation, air temperature, relative humidity, and vapor pressure agreed within 10 percent of each other for a 9-day test period at the Snively Basin site. Inaccuracies in estimates of the aerodynamic resistance to heat may have been significant in energy-budget and ET calculations for the Penman-Monteith method during periods of high instability, but not at other times. Canopy-resistance estimates for the Penman-Monteith method may have been inaccurate for times when they were estimated for winter or when vapor-pressure data were considered erroneous.

For the Snively Basin and Turnbull meadow sites, ET computed with the Bowen-ratio and Penman-Monteith methods agreed well. Squares of the correlation coefficient were 0.97 and 0.96 for the Snively Basin and Turnbull meadow sites, respectively. These good results were due mainly to usually close agreement of the daily-average canopy resistance with the canopy resistances for each time interval over the course of daylight hours.

For the Snively Basin site, a water budget was formulated with precipitation data, estimates of snow, dew, and trace precipitation, and Penman-Monteith ET estimates. This water budget was calculated for the period August 20, 1990, to September 30, 1991. Soil-water storage changes and ET were near zero at the beginning and ending dates for the water budget. The water budget showed that 101 percent of the precipitation received during this period was evaporated or transpired back to the atmosphere; 260 millimeters of precipitation and 262 millimeters of ET were estimated. Based on the instrumentation error analysis, however, in a worst-case situation (where all errors were cumulative and changed ET by ±12 percent), as little as 231 or as much as 293 millimeters of ET could have occurred. Also, if wind effects were considered, precipitation may have been as much as 273 millimeters. If dew and trace precipitation were ignored, then precipitation may have been as low as 248 millimeters. These values provide a water budget which shows that 85 to 118 percent of the precipitation became ET. However, the average of this range, 102 percent, still indicated that all the precipitation became ET. The water budget also indicated that some water from late summer precipitation events, occurring after the grasses had perished or gone dormant for the season, was held in the soil profile until the following spring, when it was transpired by plants. Only 16 percent of the ET during the water-budget period occurred from October to February, whereas 76 percent occurred from March to July; April alone accounted for 25 percent. Water budgets could not be formulated for the other sites because of the short periods of record.

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