Evaluating Evapotranspiration for Six Sites in Benton, Spokane, and Yakima Counties, Washington, May 1990 to September 1992

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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)	9.478×10^{-4}	British thermal unit
Energy-flux density		
watt per square meter (W/m^2)	5.285×10^{-3}	British thermal unit per square foot per minute
Energy and mass		
joule per gram (J/g)	0.4298	British thermal unit per pound
Flow		
cubic meter per second	15,850	gallons per minute
Length		
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
Mass		
gram (g)	2.205×10^{-3}	pound
Power		
watt (W)	3.4129	British thermal unit per hour
Pressure		
kilopascal (kPa)	0.1450	pound per square inch
Resistance		
second per meter (s/m)	0.3048	second per foot
Specific-heat capacity		
joule per gram per kelvin ([J/g]/K)	0.2388	British thermal unit per pound per degrees Fahrenheit
Temperature		
degrees Celsius (°C)	1.8°C + 32	degrees Fahrenheit
kelvin (K)	1.8 K - 459.67	degrees Fahrenheit
Velocity		
meter per second (m/s)	2.237	miles per hour
Volume		
cubic meter (m^3)	35.31	cubic foot

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

SYMBOLS AND EQUATIONS

Symbols used in text:

β	Bowen ratio, unitless
C_p	Specific heat of air, equal to 1.005 joules per gram per degree Celsius
C_s	Specific heat of soil, in joules per kilogram per degree Celsius
C_w	Specific heat of water, in joules per kilogram per degree Celsius
D	Depth, in meters
d	Zero plane displacement height (distance from surface to mean height of heat, vapor, or momentum exchange), in meters
ET	Rate of evapotranspiration, in millimeters per day
e	Vapor pressure, in kilopascals
e_s	Saturated vapor pressure, in kilopascals
ε	Ratio of molecular weight of water to air, equal to 0.622
$FX1$	Soil-heat flux measurement 1, in watts per square meter
$FX2$	Soil-heat flux measurement 2, in watts per square meter
G	Soil-heat flux, in watts per square meter
H	Sensible-heat flux, in watts per square meter
h	Canopy height, in meters
h_r	Relative humidity, in percent
K_h	Height-dependent exchange coefficient (eddy diffusivity) for heat transport, in square meters per second
K_w	Height-dependent exchange coefficient (eddy diffusivity) for water-vapor transport, in square meters per second
k	von Karman's constant, equal to 0.4, unitless
L	Latent-heat of vaporization of water, in joules per gram
LE	Latent-heat flux, in watts per square meter
LE_p	Potential latent-heat flux, in watts per square meter
P	Atmospheric pressure, in kilopascals
ρ_a	Air density, in grams per cubic meter
ρ_b	Soil bulk density, in kilograms per cubic meter
$\Re$	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, in kilopascals per degree Celsius

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, 1983, 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)	$ET = 86.4 \frac{LE}{L}$
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) (Monteith, 1965)	$LE_p = \frac{s\,(R_n - G) + \rho_a\ C_p\,(e_s - e)/r_h}{s + \gamma}$

Equations used in study text:

Number	Name and source or derivation	Equation
19.	Penman-Monteith equation (Monteith, 1965)	$LE = \left[\frac{s\left[R_n - G\right] + \left[\rho_a \, C_p \, (e_s - e)\right] / r_h}{s + \gamma\left[(r_c + r_h)/r_h\right]} \right]$
20.	Canopy resistance (Rearrangement of eq. 19)	$r_c = \frac{r_h}{\gamma}\left(\frac{1}{LE}\left[s\,(R_n - G) + \left\{ \frac{\rho_a \, C_p \, (e_s - e)}{r_h} \right\} \right] - s \right) - r_h$

Evaluating Evapotranspiration for Six Sites in Benton, Spokane, and Yakima Counties, Washington, May 1990 to September 1992

By Stewart A. Tomlinson

ABSTRACT

This report evaluates evapotranspiration for six sites in Benton, Spokane, and Yakima Counties, Washington. Three sites were located on the Arid Lands Ecology Reserve in Benton County: one at a full-canopy grassland in Snively Basin (Snively Basin site), one at a sparse-canopy grassland adjacent to two weighing lysimeters (grass lysimeter site), and one at a sagebrush grassland adjacent to two weighing lysimeters (sage lysimeter site). Two sites were located on the Turnbull National Wildlife Refuge in Spokane County: one at a full-canopy grassland in a meadow (Turnbull meadow site), the other a full-canopy grassland near a marsh (Turnbull marsh site). The last site was located in a sagebrush grassland in the Black Rock Valley in Yakima County (Black Rock Valley site).

The periods of study at the six sites varied, ranging from 5 months at the Black Rock Valley site to more than 2 years at the Snively Basin, grass lysimeter, and sage lysimeter sites. The periods of study were May 1990 to September 1992 for the Snively Basin, grass lysimeter, and sage lysimeter sites; May 1991 to September 1992 for the Turnbull meadow site; May 1991 to April 1992 for the Turnbull marsh site; and March to September 1992 for the Black Rock Valley site.

Evapotranspiration and energy-budget fluxes were estimated for the Snively Basin site, the Turnbull meadow site, and the Black Rock Valley site using the Bowen-ratio and Penman-Monteith methods. Daily evapotranspiration for the Snively Basin site was also estimated using a deep-percolation model for the Columbia Basin. The Bowen-ratio method and weighing lysimeters were used at the grass and sage lysimeter sites. The Penman-Monteith method was used at the Turnbull marsh site.

Daily evapotranspiration at the sites ranged from under 0.2 millimeter during very dry or cold periods to over 4 millimeters after heavy rainfall or during periods of peak transpiration. At all sites, peak evapotranspiration occurred in spring, coinciding with plant growth, and the lowest evapotranspiration occurred in late summer and winter, coinciding with plant dormancy and extremely hot or cold temperatures.

Water budgets for the Snively Basin, grass lysimeter, and sage lysimeter sites were based on estimates of precipitation, evapotranspiration, and surface runoff. Surface runoff was estimated at zero for all sites. For the Snively Basin site, 1991 and 1992 water budgets using Penman-Monteith evapotranspiration estimates agreed within 1 percent of the annual budgets computed using deep-percolation model estimates; daily estimates of evapotranspiration by the two methods varied considerably, however. For the Snively Basin site, 100 percent of the precipitation became ET in 1991, and in 1992, about 91 percent of the precipitation became evapotranspiration. Water budgets based on weighing lysimeter data at the grass and sage lysimeter sites agreed within 1 percent of each other for 1991 and within 5 percent of each other for 1992. For 1991, 100 percent of the precipitation became ET at both lysimeter sites. For 1992, 94 to 98 percent of the precipitation became ET at the grass lysimeter site while 98 to 99 percent of the precipitation became ET at the sage lysimeter site.

Though there were uncertainties in the methods used, recharge estimates for the Snively Basin and grass and sage lysimeter sites were of the same order of magnitude. The Penman-Monteith method (which incorporated Bowen-ratio measurements), deep-percolation model, and weighing lysimeters indicated that no recharge to subsurface systems (soil profile, unsaturated zone, and ground water) occurred in 1991 and that, in 1992, recharge to subsurface systems was probably less than 10 percent of the annual precipitation at the Snively Basin and grass and sage lysimeter sites.

INTRODUCTION

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

Background

ET is one of the most difficult components of the hydrologic cycle to quantify because of the complexity 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 under varied conditions. Some of these factors are particularly difficult to measure in semiarid areas; for example, the extremes of temperature and relative humidity are occasionally beyond the data-collection capabilities of available instruments.

In order to better estimate ET in eastern Washington, an ET study was established in August 1989 by the U.S. Geological Survey and the State of Washington Department of Ecology. New ET studies were established in 1990 and 1991 through similar agreements between the two agencies. The objectives of these studies 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 primarily describes the third phase of a study on ET for rangelands in eastern Washington. The report also provides summaries and supplemental information for the results of the first two phases. This report presents results of ET research at four grassland sites and two sagebrush sites in eastern Washington. Two of the grass sites are on the Arid Lands Ecology (ALE) Reserve near Richland; the other two are on the Turnbull National Wildlife Refuge (NWR), near Cheney (fig. 1). The ALE Reserve sites are in (1) a full-canopy (80-100 percent cover) grassland in Snively Basin (Snively Basin site), (2) a sparse-canopy (25-60 percent cover) grassland near the base of an alluvial fan adjacent to two weighing lysimeters (grass lysimeter site), and (3) a sparse-canopy sagebrush steppe adjacent to two weighing lysimeters (sage lysimeter site). The two Turnbull NWR sites are in (1) a meadow-steppe grassland (Turnbull meadow site) and (2) a marsh grassland (Turnbull marsh site). Another site is located in sagebrush steppe near the base of an alluvial fan in the Black Rock Valley near Moxee City, Wash. (Black Rock Valley site, fig. 1). This report evaluates ET data collected at these sites for various periods in 1990, 1991, and 1992. Also, the report compares methods used to estimate ET and discusses the water budgets estimated with them. Previous reports described the first phase, which focused on methods, instrumentation, and preliminary results for estimating ET from the Snively Basin site (Tomlinson, 1994) and the second phase, which provided more detailed results and discussed differences between the Bowen-ratio and Penman-Monteith methods for 1990 and 1991 data (Tomlinson, 1995).

Estimates of ET were made with the Bowen-ratio method, the Penman-Monteith method, weighing lysimeters, and a deep-percolation model for the Columbia Plateau. For estimates of ET with the Bowen-ratio and Penman-Monteith methods, instruments collected net radiation, air and soil temperatures, soil-heat flux, and soil-water content data. The Bowen-ratio method also required vapor-pressure measurements. Wind speed and relative humidity were collected for the Penman-Monteith method. Scales measured lysimeter masses to estimate weighing-lysimeter ET and precipitation. The deep-percolation model required solar radiation, air temperature, and precipitation data.

The study sites in eastern Washington were chosen for a variety of reasons. The Snively Basin site and the Turnbull meadow and marsh sites generally provided suitable conditions for using energy-balance methods of estimating ET because of their uniform canopy height, flat-to-gently sloping aspect, and extensive cover in their respective areas. The grass and sage lysimeter sites were chosen because of their proximity to weighing lysimeters. The Black Rock Valley site was chosen because of its gently-sloping aspect, extensive sagebrush cover, and relatively remote location. The grass and sage lysimeter sites and the Black Rock Valley site represent typical vegetation across much of eastern Washington.

Conversion for topographic map in Figures 1a, 1b, and 1c

FEET		METERS
1200	=	366
1400	=	427
1600	=	488
1800	=	549
2000	=	610
2200	=	671
2400	=	732
2600	=	792
2800	=	853
3000	=	914
3200	=	975
3400	=	1,036

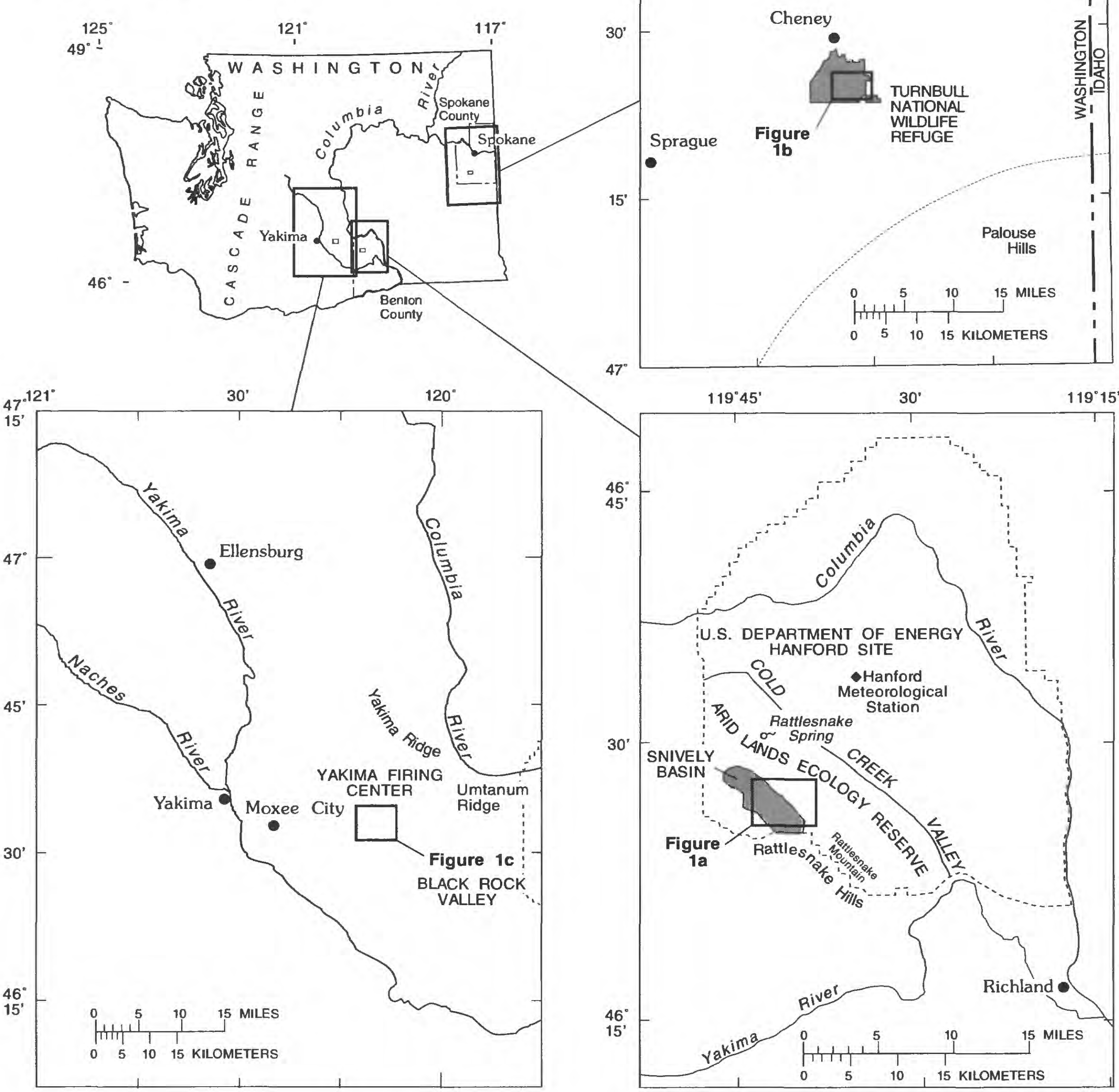

Figure 1.--Location of evapotranspiration study sites in Washington.

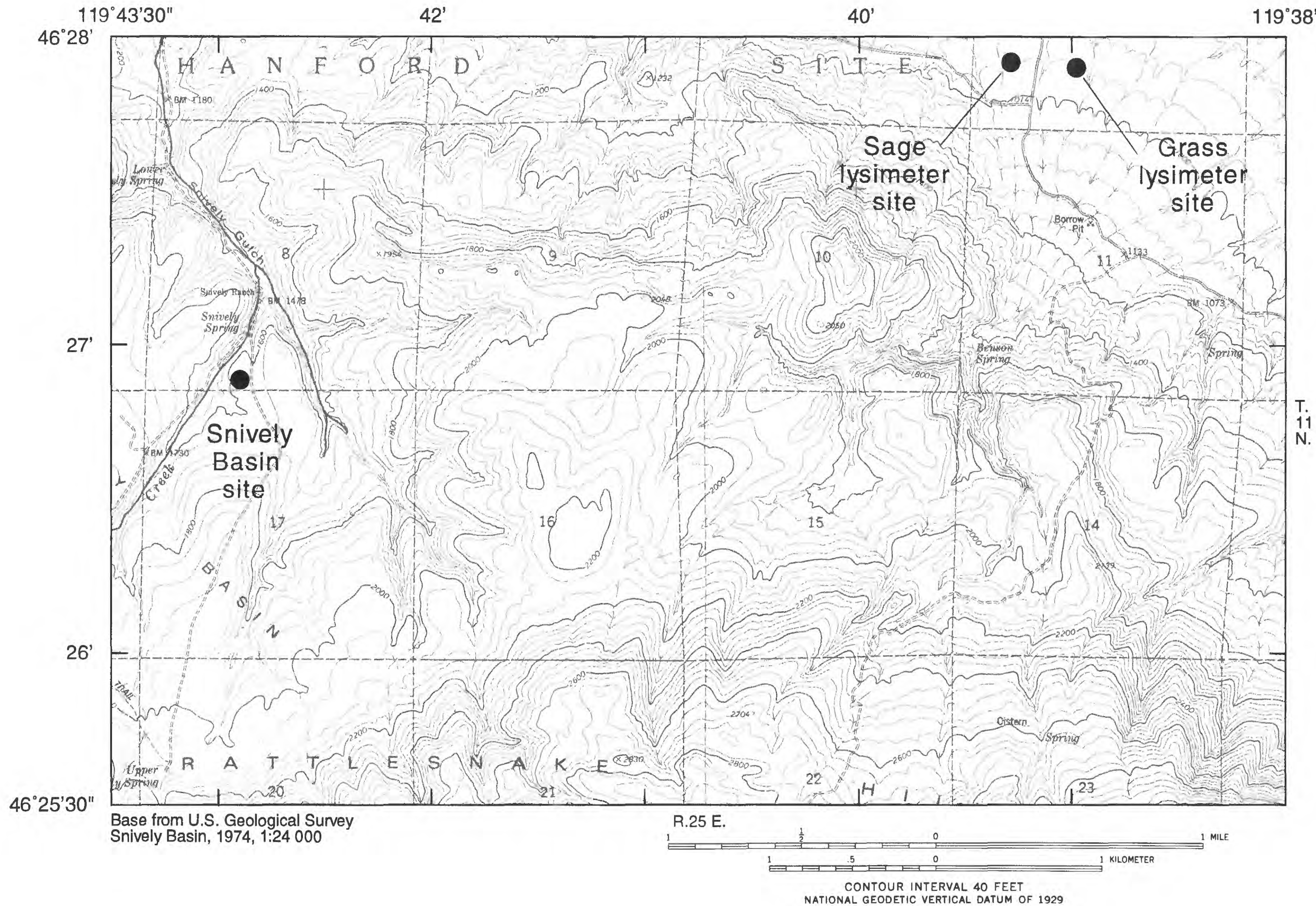

Figure 1a.--Location of grass lysimeter, sage lysimeter, and Snively Basin sites.

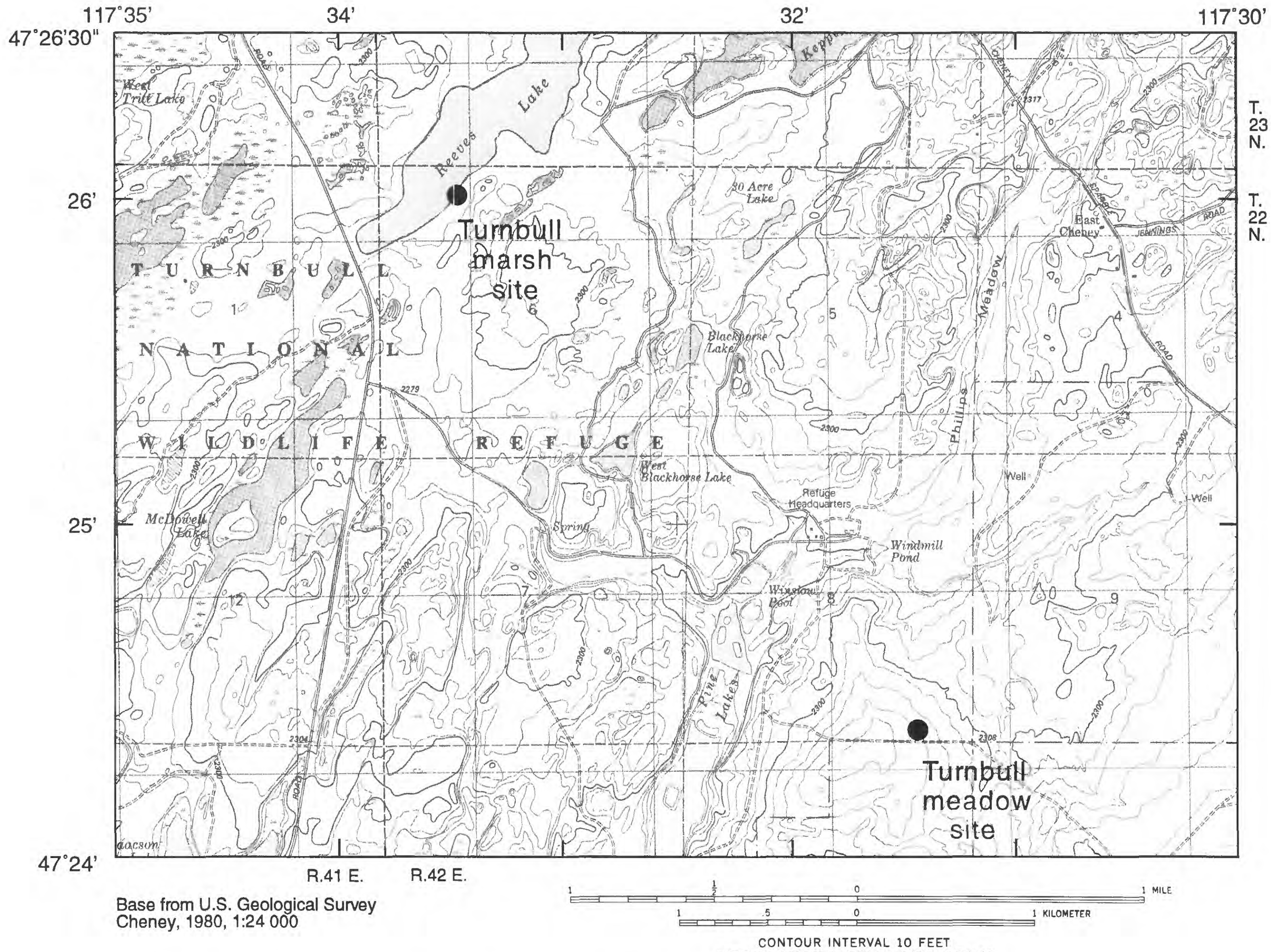

Figure 1b.--Location of Turnbull meadow and Turnbull marsh sites.

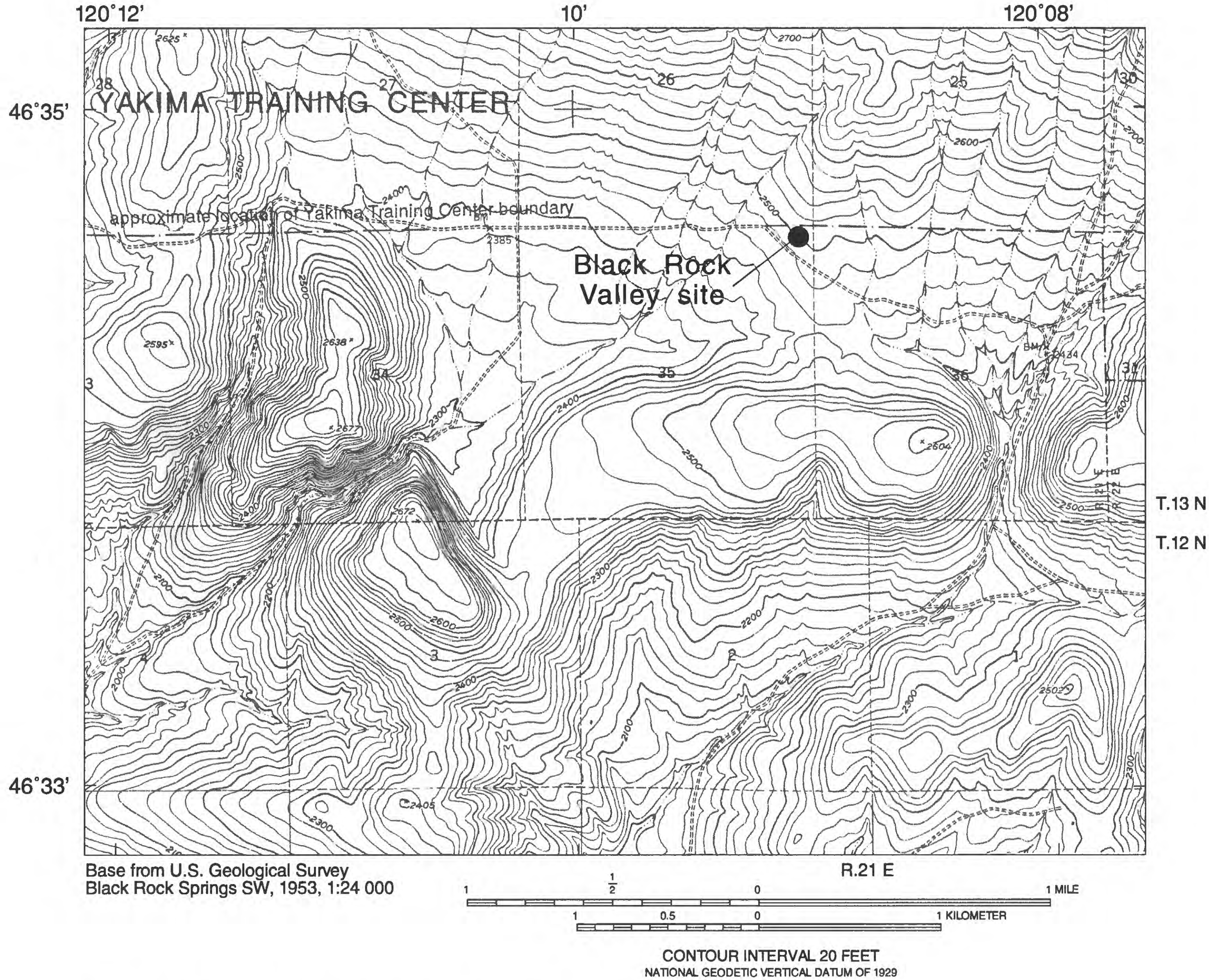

Figure 1c.--Location of Black Rock Valley site.

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Acknowledgments

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DESCRIPITON OF THE STUDY AREAS

All study sites are located in eastern Washington (see fig. 1). The Snively Basin site, grass lysimeter site, and sage lysimeter site are located in the Rattlesnake Hills on the ALE Reserve of the Hanford Site (also called Hanford Works, Hanford Reservation, or simply Hanford in many publications, maps, and documents) in western Benton County, Washington, about 64 kilometers (km) east of Yakima and 40 km west of Richland (fig. 1a). The ALE Reserve encompasses diverse topography with altitudes ranging from 134 meters (m) in the lower valleys to 1,073 m at the crest of the Rattlesnake Hills. Dominant physical 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 km to the west. The Snively Basin site is at an altitude of 494 m. About 450 m apart, the grass and sage lysimeter sites, adjacent to four weighing lysimeters (two at each site), occupy an alluvial fan 5 km northeast of the Snively Basin site, at an altitude of 293 m.

The Turnbull meadow and marsh sites are located on the Turnbull NWR about 7 km southeast of Cheney, Wash. (fig. 1b). The Turnbull NWR topography is flat to gently sloping and dotted by many permanent and seasonal lakes and ponds. Major physiographic features of the surrounding area are the Palouse Hills, about 10 km south and west, and the Spokane River, about 50 km north. The Turnbull meadow site is located in a grass meadow at an altitude of 706 m. The Turnbull marsh site is located on a grass knoll at an altitude of 696 m in a marshy area of seasonal wetlands.

The Black Rock Valley site (fig. 1c) lies at an altitude of 762 m in an area locally called The Big Flat between the Yakima Ridge, about 2.5 km to the north, and a small, unnamed ridge about 1.3 km to the south. The site is located about 14 km east northeast of Moxee City, Wash. Altitudes in the area range from 1,278 m at the crest of the Yakima Ridge to 700 m at the lowest part of the unnamed valley. Major nearby physiographic features are the Umptanum Ridge, 10 km north of the site, the Yakima River, 20 km west of the site, and the Cascade Range, 120 km west of the site.

Climate

The semiarid climate of eastern Washington results primarily from the rain-shadow effect of the Cascade Range. The Cascade crest varies between 1,200 and 3,050 m above sea level and forms an effective barrier to storms moving in from the Pacific Ocean. West of the Cascades, Olympia receives about 1,270 mm of precipitation annually, whereas east of the Cascades, Yakima receives only about 203 millimeters (mm) a year (Ruffner and Bair, 1987). From Yakima, annual precipitation gradually increases to the east with Walla Walla receiving about 383 mm and Spokane getting about 411 mm (Ruffner and Bair, 1987). Precipitation on the ALE Reserve from 1969 through 1980 ranged from about 165 mm/yr in the lower altitudes to over 280 mm 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 site (Stone and others, 1983), the estimated annual precipitation at the site averages 245 mm. For the grass and sage lysimeter sites, estimated annual precipitation averages about 209 mm on the basis of an average of two nearby stations reported by Stone and others (1983). More than 75 percent of the annual precipitation on the ALE Reserve falls from October to April, about one-fourth of it as snow. June to September is normally the driest time of year, though convective storms during this period can account for as much as 20 percent of the annual precipitation (Stone and others, 1983).

Average annual precipitation at Turnbull NWR has not been determined, but is likely to be similar to that at Cheney, only 7 km away. Annual precipitation at Cheney was measured from 1938-55 and averaged 491 mm (Maytin and Gilkerson, 1962). Annual precipitation at other nearby stations averages 373 mm at Sprague (Maytin and Gilkerson, 1962), 30 km west, and 411 mm at Spokane (Ruffner and Bair, 1987), 48 km northeast. As at the ALE Reserve sites, more than 75 percent of the total annual precipitation falls from October to April, with one-fourth to one-third in the form of snow (Ruffner and Bair, 1987). July to September is usually the driest part of the year. Thunderstorms form most often from May to September and can provide as much as 10 percent of the annual precipitation.

Because of the remoteness of the Black Rock Valley site, precipitation has not been documented there. The site's altitude of 762 m suggests that its average annual precipitation should be slightly greater than that at Moxee City (472 m), which averages 208 mm annually (Maytin and Starr, 1960). Precipitation patterns in the Black Rock Valley are probably similar to those on the ALE Reserve, 40 km to the southeast.

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

Temperature patterns at all sites are primarily continental (influenced more by air masses moving over land rather than over water), but frequent storms 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, located at Hanford (meteorological station), about 21 km from the Snively Basin site, annual temperatures average 11.7 degrees Celsius (°C). Temperature extremes at Hanford range from 46 to -33°C (Stone and others, 1983). At Moxee City, 14 km from the Black Rock Valley site, the average annual temperature is 9.1°C, and extremes range from 39 to -29°C (Maytin and Starr, 1960). At Cheney, 7 km from the Turnbull NWR sites, the average annual temperature is 8.7°C and temperature extremes range from 42 to -37°C (Maytin and Gilkerson, 1962).

Vegetation

The study sites are located in grasslands or sagebrush steppes. The Snively Basin and grass lysimeter sites on the ALE Reserve are covered by cheatgrass (*Bromus tectorum*), bluebunch wheatgrass (*Agropyron spicatum*), and Sandberg's bluegrass (*Poa sandbergii*). At the sage lysimeter site, big sagebrush (*Artemesia tridentata*) grows with these grasses. Cheatgrass, an invasive grass from Europe introduced to Washington about 1890 (Franklin and Dyrness, 1988), predominates at the Snively Basin site. Bluebunch wheatgrass and Sandberg's bluegrass predominate at the grass lysimeter site. Big sagebrush, bluebunch wheatgrass, and Sandberg's bluegrass predominate at the sage lysimeter site. Vegetation covers 80 to 100 percent of the surface at the Snively Basin site and 25 to 60 percent at the grass and sage lysimeter sites. The height of the grassland canopy was about 0.35 m at the Snively Basin site and 0.25 m at the grass lysimeter site. At the sage lysimeter site, the average height of the sagebrush was 1.0 m and of the grasses 0.25 m. At the Snively Basin site, roots from the grasses generally extended into the soil about 0.20 m, although some roots were found as deep as 1.1 m. Franklin and Dyrness (1988) found cheatgrass roots as deep as 0.97 m. Sagebrush has a taproot that can penetrate 1 to 4 m, but a caliche layer at 2 m at the sage lysimeter site probably limits rooting to that depth.

Other plants occurring in small numbers among the grasses and sagebrush on the ALE Reserve include rabbitbrush (*Chrysothamnus nauseouses*), bitterbrush (*Purshia tridentata*), Carey's balsamroot (*Balsamorhiza careyana*), showy phlox (*Phlox speciosa*), and lupine (*Lupinus sp.*). Sagebrush is probably the climax (stable stage of plant succession) species on the ALE Reserve, but it is fire-sensitive (Franklin and Dyrness, 1988). A major fire in 1984, which burned 80 percent of the ALE Reserve (Rickard and others, 1988), eliminated sagebrush at the Snively Basin and grass lysimeter sites. Grasses cover the surface in all directions for distances of 400 m to 3 km and further at the Snively Basin and grass lysimeter sites. The sage lysimeter site is located at the northeastern edge of a large area of sagebrush. Grasses begin about 30 to 100 m north and east of the sage lysimeter site, probably corresponding with the edge of the 1984 burn. Sagebrush extends over 1 km to the west and south of the sage lysimeter site.

Small areas of riparian vegetation grow near springs on the ALE Reserve. Areas such as Snively Gulch have small numbers of woody plants, including trees. Plant identification was aided by Hayes and Garrison's "Key to Important Woody Plants of Eastern Oregon and Washington" (Hayes and Garrison, 1960). Included among these trees are Black cottonwood (*Populus trichocarpa*), Common chokecherry (*Prunus virginiana*), Columbia hawthorne (*Crataegus columbiana*), several species of willow (*Salix sp.*), and a naturalized exotic, White poplar (*Populus alba*). At the weighing lysimeter sites, the closest trees are several naturalized Siberian elms (*Ulmus pumila*) at an abandoned ranch about 3.2 km away.

At the ALE Reserve sites, vegetation grows most rapidly during the wet winter and spring seasons. Growth peaks from March to May, when ET is also at its maximum because of the transpiration from the growing vegetation. Dryer summer weather beginning in June slows growth and ultimately causes the grasses to seed and perish or go dormant. At this time, sagebrush begins to lose a number of leaves in response to the drying conditions. In late summer and early fall, usually the driest time of year, sagebrush blooms while grasses are completely dormant. Grasses begin growing again in fall when the first major precipitation occurs.

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*), Merrill's bluegrass (*Poa ampla*), Sandberg's 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 very thick and lush and the canopy height averages 0.91 m. The grasses extend at least 600 m in all directions from the Turnbull meadow site. Beyond that distance to the west and north, small patches of Ponderosa pine (*Pinus ponderosa*) mix with the grasses.

The Turnbull marsh site is located in a mixed grass community on a peninsular knoll bordered by a seasonal wetland on three sides. The knoll rises about 3 m above the bed of the seasonal wetland and is about 4.5 m wide and 9 m long. The vegetation includes a mixture of grasses including 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 m high. The mixed grasses extend over 500 m to the north, east, and west and about 300 m to the south.

A variety of trees and shrubs also grow on the Turnbull NWR. Thickets of round-leaved snowberry (*Symphoricarpos albus*) grow near the Turnbull meadow and marsh sites. The predominant tree in the dryer 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 remain dormant during the winter. The grasses begin growth at the Turnbull meadow site in March, with maximum growth from May through mid-July. Dry summer weather from mid-July through September slowly causes the vegetation to seed and perish or go dormant. At the Turnbull marsh site, plant growth also begins in March; however, the water table remains high enough for most vegetation to remain active into September. Freezing temperatures usually begin in September or October causing vegetation remaining in growth to go dormant or perish.

At the Black Rock Valley site, bluebunch wheatgrass, Sandberg's bluegrass, and big sagebrush predominate. Stiff sagebrush (*Artemesia rigida*) and desert buckwheat (*Eriogonum thymoides*) also grow in areas surrounding the site. Relatively few other plants grow near the site—there is a noticeable absence of annuals and non-grass perennials. The grasses average 0.4 m in height and the sagebrush 0.9 m in height. Sagebrush-covered areas extend over 3 km to the west, north, and east of the site. Towards the south and southwest, sagebrush extends about 400 m, where an abandoned field covers areas further away. The plant growth cycle is similar to that of the ALE Reserve sites, with the exception that growth begins about 2 to 4 weeks later in spring because of colder temperatures resulting from the higher elevation of the Black Rock Valley site. ET is also higher in late summer and early fall at the Black Rock Valley site, compared with the ALE Reserve sites.

Soils and Geology

All study sites are located in the Columbia Plateau physiographic province. The major surficial rock features of this area are numerous layers of basalt, the result of lava flows during the Miocene and Pliocene epochs, with thin sedimentary and volcanic ash interbeds. Silt, gravel, 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 epoch (Alt and Hyndman, 1984) cover much of the lower elevations of the Columbia Plateau. Windblown loess was deposited over much of the Plateau during the Pleistocene and Holocene epochs.

The ALE Reserve is 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 consists of basalt.

The predominant soil at the Snively Basin site, Ritzville silt loam, is a dark grayish-brown silt-loam soil that develops under grassland from silty wind-laid deposits mixed with small amounts of volcanic ash (Hajek, 1966). Ritzville silt loam is generally greater than 1.5 m thick and has high water-holding capacity, moderate permeability, and low runoff potential (U.S. Department of Agriculture, 1971).

Warden silt loam predominates at the grass and sage lysimeter sites. Permeability, water-holding capacity, and runoff potential of Warden silt loam are similar to those of Ritzville silt loam. This soil differs from the Ritzville silt loam in that it becomes strongly calcareous about 0.5 m below the surface. Granitic boulders are found in many areas with Warden silt loam soil. These boulders were carried to the area with glacial ice by the Spokane Flood. Hajek (1966) reports that Warden soils intergrade to Ritzville soils at an altitude of approximately 366 m.

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 Spokane Flood created many various-sized basins that are the present-day coulees, potholes, ponds, and lakes in the area. The predominant orientation of these features is southwest to northeast, parallel with the main flow direction of the Spokane Flood. Bedrock is basalt.

The Turnbull meadow site is covered by Hesseltine silt loam. This soil developed from gravelly outwash materials with a thin mantle of loess (Maytin and Gilkerson, 1962). Hesseltine silt loam covers nearly level to gently sloping areas, and basalt bedrock is usually about 0.3 m below the surface.

The Turnbull marsh site is located on a peninsular knoll that was constructed in the 1960's, and the soil making up the knoll is probably a mixture of several soil types. From samples taken of the top 0.2 m of the soil profile, Saltese muck appears to be the predominant soil type. The Saltese muck typically forms in areas having a high water table (Maytin and Gilkerson, 1962). The first 0.5 m of depth is composed of a black, granular, permeable muck. Underneath are reddish-brown layers of raw peat derived from tules, reeds, and sedges.

Willis silt loam lies at the Black Rock Valley site. It is a moderately deep, well-drained soil formed from loess (U.S. Department of Agriculture, 1985). Permeability of the Willis silt loam is low to moderate, water-holding capacity is high, and runoff potential is moderate (U.S. Department of Agriculture, 1985). A hardpan exits in the soil at a depth of 0.5 to 1.0 m, and bedrock is basalt.

Hydrology

At all study sites, most precipitation is lost to ET. For the sites on the ALE Reserve, there is probably little ground-water recharge except during very wet periods in some winters, when ET is minimal. In a water-balance study for a sandy soil at the Hanford Site, Gee and Kirkham (1984) reported that 5 cm of water penetrated 3.5 m 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 m than areas covered with sagebrush. Consequently, grass-covered areas, such as the Snively Basin and grass lysimeter sites, would be expected to allow more recharge than areas covered with the deeper-rooted sagebrush, which would remove deeper soil moisture.

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

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

The closest spring to the grass and sage lysimeter sites is Benson Spring. It is located 2 km south of the sites and flows at an estimated 6.2×10 m^3/s (10 gallons per minute) (Schwab and others, 1979).

At the Turnbull NWR, some ground-water recharge probably occurs during most years, though timing and amounts are variable. In a study of southern Spokane County, Olson and others (1975) estimated that about 2 to

3 percent of the annual precipitation reached aquifers. Recharge occurs mainly through infiltration along stream channels and from wetlands in the area. Lakes and basins in the area refill through a combination of ground-water discharge and overland runoff.

From November through February at the Turnbull NWR, ET rates are very low (because of the cold weather), while precipitation is at its highest for the year. Under these conditions, seasonal basins and lakes are refilled, and marshes and other wetlands are reflooded. The basin and lakes refill primarily as a result of ground-water discharge (J.J. Vaccaro, U.S. Geological Survey, oral commun., 1995) as water tables rise due to precipitation that infiltrates subsurface systems (soil moisture and ground water). Some precipitation may become overland runoff and contribute to refilling the basins, lakes, and marshes during heavy rain or from rain falling on frozen ground. Part of the recharged soil moisture is significantly lost to ET from about March to July. By August or September, the lakes and wetlands have much lower water levels or, in some cases, have become dry. The amount of water-level decline is variable from year to year, depending on precipitation, air temperature, solar radiation and other meteorological factors. Autumn rains usually start in October, beginning the cycle again.

At the Black Rock Valley site, there are several seeps west and east of the site that flow southward from the Yakima Ridge through canyons to the main part of the Black Rock Valley. One of these canyons is about 2.5 km west of the site. Another canyon lies 4 km east of the site. Normally the drainages in these two canyons are dry in the upper reaches, but water may run in them during and shortly after intense rainfalls. No measurements of these drainages are available. Depth to the water table is not known at the Black Rock Valley site, but it must be fairly close to the surface in an area about 5 km southeast of the site, where several small cottonwood and willow trees are growing. In a field about 1 km west of the Black Rock Valley site, however, water was first reported at about 150 to 200 m below the surface while drilling a well (S. Martinez, oral commun., 1994).

METHODS OF ESTIMATING EVAPOTRANSPIRATION

Several methods of data collection and analysis were used in this study to estimate ET; instruments, energy-budgets, weighing lysimeters, and the Columbia Plateau deep-percolation model (model). Instruments measured solar radiation, net 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 with 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 ET with the Penman-Monteith method. Precipitation and solar radiation data were not required for the Bowen-ratio or Penman-Monteith methods; those data assisted in interpreting the other data such as relative humidity and soil-heat flux and were also used in the model. ET was calculated from the weighing lysimeters by determining daily weight differences in the lysimeters. Model ET estimates required solar radiation, air temperature, and precipitation data.

ET was estimated for different periods with a different combination of methods at each site (fig. 2). For the Snively Basin site, instruments collected data from May 30, 1990 to September 30, 1992, and ET was estimated with the Bowen-ratio and Penman-Monteith methods. Also, the model was used to estimate ET at the Snively Basin site for August 20, 1990 to September 30, 1992. At the grass and sage lysimeter sites, weighing lysimeters collected data from May 1, 1990 to September 30, 1992. In addition, Bowen-ratio data were collected from April 1 to May 14, 1991 at the grass lysimeter site and from April 30 to September 30, 1992 at the sage lysimeter site. For the Turnbull meadow site, instruments collected data from May 15, 1991 to September 29, 1992, and ET was estimated with the Bowen-ratio and Penman-Monteith methods. For the Turnbull marsh site, instruments collected data from May 15, 1991 to April 29, 1992, and ET was estimated with the Penman-Monteith method. For the Black Rock Valley site, instruments collected data from March 26 to September 30, 1992, and ET was estimated with the Bowen-ratio and Penman-Monteith methods.

1990

	January	February	March	April	May	June	July	August	September	October	November	December
Grass Lysimeter Site												
Weighing lysimeters*	--	--	--	--	✔	✔	✔	✔	✔	✔	✔	✔
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Sage Lysimeter Site												
Weighing lysimeters*	--	--	--	--	✔	✔	✔	✔	✔	✔	✔	✔
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Snively Basin Site												
Bowen-ratio method	--	--	--	--	--	✔	✔	✔	✔	✔	--	--
Penman-Monteith method	--	--	--	--	--	✔	✔	✔	✔	✔	✔	✔
Deep-percolation model	--	--	--	--	--	--	--	✔	✔	✔	✔	✔
Turnbull Meadow Site												
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Penman-Monteith method	--	--	--	--	--	--	--	--	--	--	--	--
Turnbull Marsh Site												
Penman-Monteith method	--	--	--	--	--	--	--	--	--	--	--	--
Black Rock Valley Site												
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Penman-Monteith method	--	--	--	--	--	--	--	--	--	--	--	--

1991

	January	February	March	April	May	June	July	August	September	October	November	December
Grass Lysimeter Site												
Weighing lysimeters*	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Bowen-ratio method	--	--	--	✔	✔	--	--	--	--	--	--	--
Sage Lysimeter Site												
Weighing lysimeters*	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Snively Basin Site												
Bowen-ratio method	--	--	✔	✔	✔	✔	✔	✔	✔	✔	--	--
Penman-Monteith method	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Deep-percolation model	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Turnbull Meadow Site												
Bowen-ratio method	--	--	--	--	✔	✔	✔	✔	✔	✔	--	--
Penman-Monteith method	--	--	--	--	✔	✔	✔	✔	✔	✔	✔	✔
Turnbull Marsh Site												
Penman-Monteith method	--	--	--	--	✔	✔	✔	✔	✔	✔	✔	✔
Black Rock Valley Site												
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Penman-Monteith method	--	--	--	--	--	--	--	--	--	--	--	--

1992

	January	February	March	April	May	June	July	August	September	October	November	December
Grass Lysimeter Site												
Weighing lysimeters*	✔	✔	✔	✔	✔	✔	✔	✔	✔	--	--	--
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Sage Lysimeter Site												
Weighing lysimeters*	✔	✔	✔	✔	✔	✔	✔	✔	✔	--	--	--
Bowen-ratio method	--	--	--	--	✔	✔	✔	✔	✔	--	--	--
Snively Basin Site												
Bowen-ratio method	--	--	✔	✔	✔	✔	✔	✔	✔	--	--	--
Penman-Monteith method	✔	✔	✔	✔	✔	✔	✔	✔	✔	--	--	--
Deep-percolation model	✔	✔	✔	✔	✔	✔	✔	✔	✔	--	--	--
Turnbull Meadow Site												
Bowen-ratio method	--	--	--	--	--	--	--	--	--	--	--	--
Penman-Monteith method	✔	✔	✔	✔	✔	✔	✔	✔	✔	--	--	--
Turnbull Marsh Site												
Penman-Monteith method	✔	✔	✔	✔	--	--	--	--	--	--	--	--
Black Rock Valley Site												
Bowen-ratio method	--	--	✔	✔	✔	✔	✔	✔	✔	--	--	--
Penman-Monteith method	--	--	--	--	✔	✔	✔	✔	✔	--	--	--

Figure 2.--Methods estimating evapotranspiration and periods of data collection at the study sites; ✔ denotes period of collection; *, data collected and provided by Battelle, Pacific Northwest Laboratories.

Instrumentation

Figure 3 shows the instruments used to collect data needed to estimate ET at the six sites. Table 1 describes each of the instruments. More detailed information on the instruments is presented by Tomlinson (1994) in the first phase report for this study. Two sets of instruments collected data at the Snively Basin site, the Turnbull meadow site, and Black Rock Valley site (fig. 3). One set of instruments collected data primarily for the Bowen-ratio method, and the other set of instruments primarily gathered data for the Penman-Monteith method. Only Bowen-ratio instruments collected data at the grass and sage lysimeter sites. At the Turnbull marsh site, only Penman-Monteith instruments collected data. The Bowen-ratio set of instruments 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 air intakes, and two air-temperature thermocouples. The Penman-Monteith set of instruments included one data logger, one net radiometer, one pyranometer, one anemometer, one air 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 samples during visits at all sites in order to estimate the soil-water content which was used to estimate the soil-heat storage term for the Bowen-ratio and Penman-Monteith methods.

Each set of instruments was mounted on a separate tripod and mast. Soil-heat-flux transducers and averaging soil-temperature probes were installed below the soil surface. To estimate the soil-heat storage term for both methods, soil samples collected from all sites were analyzed for water content.

Several problems with the instrumentation resulted in incomplete or erroneous data. Burrowing animals damaged the soil-heat-flux transducer wires at the Snively Basin, Turnbull meadow, Black Rock Valley, and sage lysimeter sites on several occasions during the period of study. 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, which was replaced September 6, 1990. Ice formed on the mirror of the cooled-mirror hygrometer on several occasions at the Snively Basin site in October 1990 and September 1991; at the Turnbull meadow site in July and September 1991; at the sage lysimeter site in May, June, July, and September 1992; and at the Black Rock Valley site in May and June 1992. An animal chewed through the battery cable at the sage lysimeter site on July 31, 1992; this was repaired on August 14, 1992. Other inexplicable problems occurred with the cooled-mirror hygrometer at the sage lysimeter site that resulted in invalid vapor-pressure data for most of the May to September 1992 data-collection period. The cooled-mirror hygrometer at the sage lysimeter site was subsequently sent to the manufacturer for repair, where problems with the cooled mirror were corrected. When instrument problems occurred intermittently, erroneous data values were replaced with estimates made by averaging valid values on each side of the erroneous one. Differences between like instruments probably produced little error in the resultant ET estimates. In a study conducted from September 5-13, 1991 at the Snively Basin site, like instruments were compared (Tomlinson, 1995). Net radiometers differed by 4 percent, soil-heat-flux transducers by 28 percent, air temperature by 4 percent, and vapor-pressure by 10 percent (2 days only). The study determined that if all instruments varied by the maximum amount, only a 12 percent change in ET would result from the Bowen-ratio method. More likely, it is less than 12 percent because some errors would probably mitigate others.

Energy-Budget Methods

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

ET involves a phase change of water from liquid to vapor (a process requiring energy) and the movement of that vapor into the atmosphere. It can be conceptualized as taking place as part of an energy budget, which has four main flux components; net radiation, latent-heat flux, sensible-heat flux, and soil-heat flux. Field measurements of the energy-budget components encompass a layer with its upper boundary just above the plant canopy and its lower boundary just below the soil surface (fig. 4); in this report, this layer is called the canopy layer. In the energy budget equation (eq. 1, located at the beginning of the report), net radiation equals the sum of the other three fluxes.

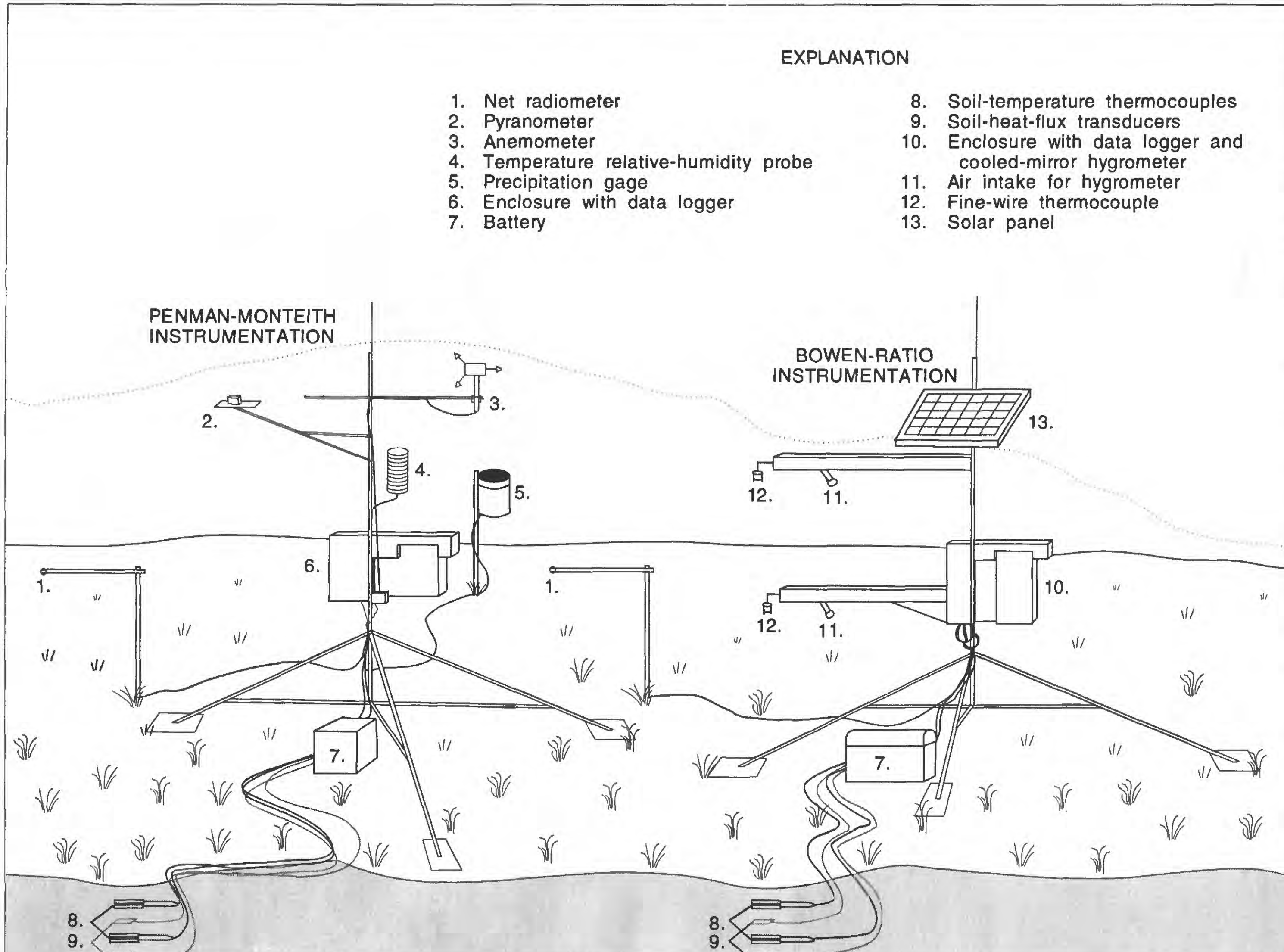

Figure 3.--Instrumentation setup at the evapotranspiration sites.

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

Instrument type	Function	Manufacturer (Model)
Data logger	Scan instruments, record and process data	Campbell Scientific (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)

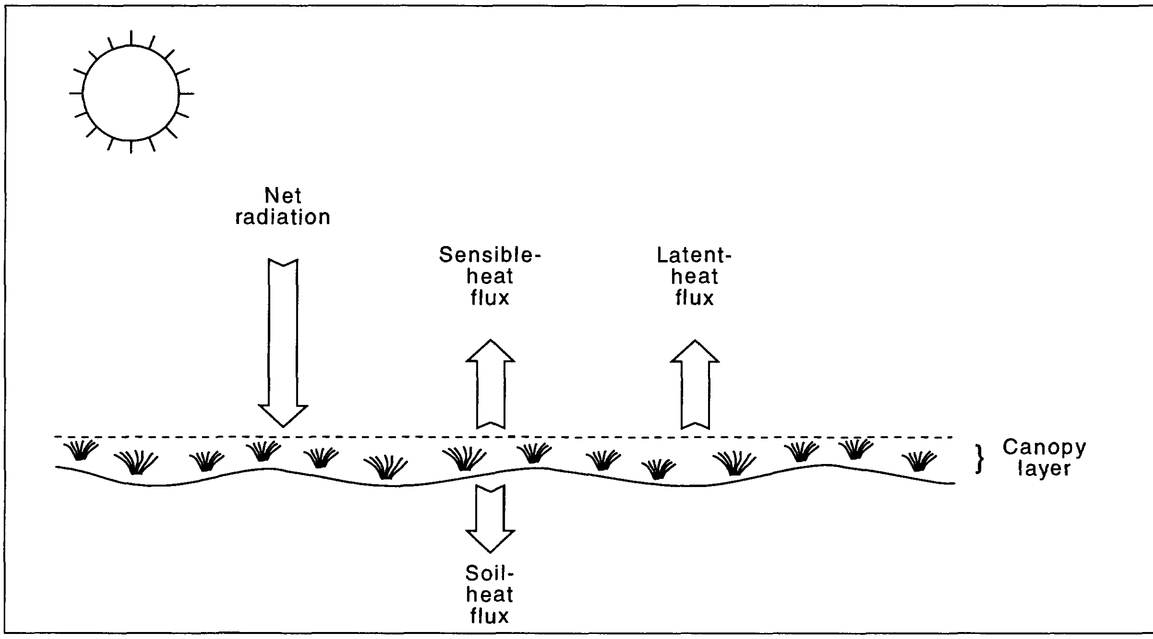

Figure 4.--Energy budget in the canopy layer.

Defined as 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), net radiation, R_n, provides the major energy source for the energy budget. Net radiation 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 and movement of water. It is the product of the latent heat of vaporization of water and 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, is a turbulent, temperature-driven heat flux resulting from differences in temperature between soil and vegetative surfaces and the atmosphere. In this report, sensible-heat flux is considered positive when heat is transferred upward from the surface across the upper boundary of the canopy layer. During the daytime, positive sensible-heat flux is often the result of surface heating. At night, sensible-heat flux is often less than zero, the result of surface cooling.

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

One of the requirements for use of energy-budget methods is that the wind must move over a sufficient distance of like vegetation and terrain before it reaches the sensors. This distance is termed fetch, and the fetch requirement is generally considered to be 100 times the height of the sensors (Campbell, 1977, p. 40). At the study sites, the maximum sensor height above the canopy was 3.0 m. Therefore, a minimum of 300 m of similar vegetation and terrain should be present at the sites. This requirement was met in all directions at all of the study sites except for one direction at the sage lysimeter site and possibly one direction at the Black Rock Valley site. The sage lysimeter site is at the northern end of an extensive patch of sagebrush but only about 30 to 100 m from an area with grasses but no sagebrush. Winds coming directly from the south passed over this grassy area before reaching the instruments at the sage lysimeter site, so there may have been times during the study period when fetch requirements were not met. To compare Bowen-ratio ET estimates with weighing- lysimeter ET, it was necessary to set the Bowen-ratio instruments in this part of the sagebrush patch so they could collect data adjacent to the weighing lysimeters. Whether the differences between the non-sagebrush area and the sagebrush area were sufficient to affect the data that were collected is not known because most of the vapor-pressure data collected at the site was erroneous because of sensor malfunctions. From weighing-lysimeter ET results at the grass and sage lysimeters sites, however, ET appeared to be nearly the same in sage and non-sage areas. At the Black Rock Valley site, the fetch requirement is technically met; however, an abandoned field is about 400 m southwest of the site. Since winds often come from the southwest and wind speeds are frequently over 10 m/s, there might be some situations in which the fetch requirement was greater than that generally accepted. During periods of high winds from the southwest, this might have resulted in unrepresentative data for the site.

Bowen-Ratio Method

The Bowen-ratio method incorporates energy-budget principles and turbulent-transfer theory (Brutsaert, 1982, p. 210-214). The ratio of sensible- and latent-heat fluxes of the energy-budget equation (eq. 1) is known as the Bowen ratio (Bowen, 1926). Bowen showed that this ratio, β (eq. 6), could be calculated from vertical gradients of temperature and vapor over a surface (eq. 7) under certain conditions. Often the gradients are approximated from air temperature and vapor-pressure measurements taken at two heights above the canopy. The Bowen-ratio method assumes that there is no net horizontal advection of energy. If there is no net horizontal advection of energy, 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-Monteith Method

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

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

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

Canopy Resistance

The canopy resistance is a combination of the resistances to evaporation due to dry soil and to transpiration due to stomatal closure or senescence. The canopy resistance is not easily measured, however. In practice, the canopy resistance is not measured directly, but determined by computing the latent-heat flux by other means, such as the Bowen-ratio method, for short periods, and then solving the Penman-Monteith equation for the canopy resistance, which was the approach used in this study. Using this approach, values for the canopy resistance ranged from near zero during and shortly after periods of heavy rainfall to over 30,000 seconds per meter (s/m) during extremely hot, dry periods (Tomlinson, 1994; Tomlinson, 1995).

For periods when Bowen-ratio data were available to calibrate the Penman-Monteith equation for the canopy resistance, daily average canopy resistances were computed with canopy resistances calculated for each 20-minute or 60-minute interval from 8 o'clock in the morning to 5 o'clock in the afternoon, when ET was highest (Tomlinson, 1994; Tomlinson, 1995). This daily average canopy resistance was then used in the Penman-Monteith equation for all intervals to compute a daily ET value. This procedure allowed ET estimates to be made for days when Bowen-ratio data were available for only part of the day.

For the Snively Basin site, during periods where no Bowen-ratio data were available, such as winter, the canopy resistance was simply estimated (educated guess) after taking into consideration data such as soil moisture, air temperature, relative humidity, and precipitation. For instance, if the relative humidity was 100 percent (fog), if there was snow on the ground, or if there was rainfall, the canopy resistance was assumed to be zero because of an abundant water supply (equivalent to potential ET). For subsequent days with above-freezing temperatures and no precipitation, canopy resistances were increased with educated guesses on the basis of spring and summer drying-off conditions, to a maximum of 3,000 s/m. This value seemed reasonable on the basis of canopy resistances for similar conditions in late summer. These methods of estimation were used because no simple function was found correlating canopy resistance with any one variable. The best correlation found was with soil moisture, but the r^2 (square of the correlation coefficient) was only 0.63.

For the Turnbull meadow and marsh sites, good correlation between soil moisture and canopy resistance (Tomlinson, 1995) allowed estimates of canopy resistance to be made on the basis of soil moisture for all periods of the year where no Bowen-ratio data were available. For the Turnbull meadow site's soil moisture-canopy resistance relation, the r^2 was 0.82 (Tomlinson, 1995).

Aerodynamic Resistance

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

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

The equation used in this study to estimate r_h (eq. 17) requires the measurement of wind speed at only one height. However, the equation is applicable only during neutral conditions. For unstable conditions, a profile stability correction for sensible heat should be added to the equation. However, solving for the profile stability correction involves a series of extremely complex iterative calculations. Though using equation 17 without the correction for unstable conditions may overestimate r_h by as much as a factor of two in some conditions (D.I. Stannard, U.S. Geological Survey, written commun., 1992), some investigators have 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).

For this study, using an r_h value in error by as much as 100 percent has little impact on the calculations of ET. Doubling r_h for one time step (20 or 60 minutes) in the Penman-Monteith equation for the Snively Basin site increased the daily average canopy resistance by 30 percent and the daily ET estimate by 3.5 percent (Tomlinson, 1995). Three and one-half percent is within range of the precision errors introduced by the instruments (Tomlinson, 1995). Furthermore, the data showed that the canopy resistance frequently varied by 30 percent or more during each 20 or 60-minute time step, even during neutral conditions. Using the stability-correction factor in this study would not have resulted in more accurate estimates of ET; therefore, it was not used.

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

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, z_h, in meters, is a function of the momentum roughness length. The terms d, z_m, and z_h are difficult to measure, but they may be determined graphically from wind profiles or calculated through empirical equations. For 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 m canopy is somewhat less than dense. Therefore, a value for d lower than 0.64 times h seems reasonable because the level of heat, vapor, or momentum exchange will be closer to the surface than for a truly dense canopy. For the Snively Basin site, 0.50 times h was chosen, giving a d of 0.18 m. The value chosen for d does not have a major effect on the resulting value for r_h in equation 17 because d is much smaller than the z of 3.0 m. Using a d of zero changes the overall r_h less than 2 percent from r_h obtained with a d of 0.18 m, 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 m 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 m. This value seems reasonable compared with tabled z_m values for full-cover grasses of 0.001 m to 0.0065 m in Brutsaert (1982, p. 114). Campbell (1977, p. 39) states that z_h equals 0.2 z_m, so z equals 0.0008 m for the Snively Basin site. Wind speed was collected at height z, 3.0 m above the canopy. For the Snively Basin site, 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 when snow covered the vegetation, d was estimated to be zero (flat surface), z_m was estimated to be 0.0001 m (Stull, 1988, p. 380), and z_h was 0.0002 m. 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 made on the basis of the height of the vegetation. Thus, Campbell's (1977, p. 38) estimate for d ($d = 0.64\ h$) was used. For dense canopies, Campbell (1977, p. 39) estimates the momentum roughness length as $z_m = 0.13\ h$ and the heat-transfer roughness length as $z_h = 0.2\ z_m$.

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

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

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

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

Snow did not completely cover the plants during the winter of 1991-92 at the Turnbull meadow and marsh sites; therefore, no adjustments were made for snow conditions at these sites.

For the Black Rock Valley site, no wind-speed profile measurements were made to determine z_m. Estimates of z_m over 0.75-m high greasewood in Nevada were 0.07 m from a Leaf-Area-Index method and 0.06 m using wind-speed profiles (Nichols, 1992, p. 229-233). From an analysis of turbulence over a sparsely-vegetated canopy with 1-m-high greasewood in Colorado, z_m was estimated at 0.05 m (Stannard, 1993, p. 1381-1383). An average of 0.06 m seems reasonable to use for the Black Rock Valley site because of the similarity in canopy height—the average shrub height at the Black Rock Valley was 0.81 m compared with 0.75 m and 1 m at the Nevada and Colorado sites, respectively. The value for z_h at the

Black Rock Valley site was estimated from $\ln\left(\frac{z_m}{z_h}\right) = 2$ (Garratt and Hicks, 1973, fig. 2). This method has been used at other sparse-canopy sites (Stannard, 1993, p. 1383). The zero-plane displacement, d, was estimated at zero for the Black Rock Valley site because of the wide spacing of the shrubs and sparseness of the grass subcanopy. From the above estimated values for d, z_m, and z_h in equation 17 for the Black Rock Valley site,

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

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

Weighing Lysimeters

Weighing lysimeters provide the most direct method for estimating evapotranspiration (Kirkham and others, 1991). When the lysimeter soil profile and vegetation type 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 the mass reflect evapotranspiration and precipitation. Monolith weighing lysimeters installed and maintained on the ALE Reserve by Battelle, Pacific Northwest Laboratories, use scales that are sensitive to 50 grams, equivalent to 0.02 mm of water (Gee and others, 1991). The surface dimensions of the inner boxes of the ALE Reserve lysimeters are about 1.5 m^2 and range from 1.4 to 1.6 m deep (Kirkham and others, 1991).

The scales that weigh the monoliths produce voltages that are measured every 10 seconds and averaged every hour (Gee and others, 1991). The hourly average voltages are converted to weight in kilograms by adding 1 to the voltage and multiplying the result by a calibration factor (R. Kirkham, Battelle, PNW Laboratories, written commun., 1991). The factors for each lysimeter, in kilograms per volt (kg/v), are as follows:

Lysimeter number	Site	Factor (kg/v)
1	Grass	4650.2527
2	Grass	4646.3382
3	Sage	4651.5727
4	Sage	4645.2527

The difference between the weights can then be converted to ET (negative weight difference) or precipitation (positive weight difference) in millimeters as follows: divide the weight difference, in kilometers per hour, by 23,104 cm^2 (the area of each lysimeter); multiply the result by 10,000 $mm/kg/cm^2$ to obtain a value in millimeters per hour. Sum the hourly weight losses (negative differences) to obtain ET and add the weight gains (positive weight differences) to obtain precipitation. An alternate method to obtain daily ET is to use the above procedure with midnight-to-midnight voltage values, and subtract daily precipitation.

Estimating ET and precipitation using the weighing-lysimeter data was usually fairly straightforward, but there were some exceptions. The process of calculating daily ET and precipitation was normally a simple matter of summing the hourly weight losses (ET) and weight gains (precipitation). On some occasions, however, such as during light rainfalls, precipitation and ET probably occurred during the same hour and the net hourly result was the greater of ET or precipitation. On other occasions, weight gains and losses might have been due to soil or snow movement during windstorms or due to animal trespass. Also, during very dry periods, the lysimeters showed a tendency to gain weight at night, possibly the result of dew formation or heating and cooling effects on the lysimeter monoliths (R. Kirkham, Battelle, PNW Laboratories, oral commun., 1993). Unless these circumstances were very clear, it was not possible to account for these phenomena in the data.

Deep-Percolation Model

Bauer and Vaccaro (1987) developed a deep-percolation model for estimating ground-water recharge and used that model to make such estimates for the Columbia Plateau (Bauer and Vaccaro, 1990), which includes the ALE Reserve and Black Rock Valley. The deep-percolation model computes transpiration, soil evaporation, snow accumulation, snowmelt, sublimation, and evaporation of intercepted moisture using data for precipitation, daily maximum and minimum air temperature, streamflow, soils, land use, and elevation. The model (Bauer and Vaccaro, 1990) makes water-budget calculations using the formula

$$PRCP = RCH + EVINT + EVSOL + EVSNW$$
$$+ PTR + RO + \Delta INT + \Delta SNW + \Delta SNM$$

where

$PRCP$	=	precipitation,
RCH	=	water percolating below the root zone,
$EVINT$	=	evaporation of foliage-intercepted moisture,
$EVSOL$	=	evaporation from bare soil,
$EVSNW$	=	snowpack sublimation,
PTR	=	transpiration,
RO	=	surface runoff,
ΔINT	=	change of moisture on foliage surfaces,
ΔSNW	=	change of snowpack, and
ΔSM	=	change of soil water in the root zone.

The deep-percolation model makes daily simulations for individual grid cells for zones ranging in size from 52 to 6,200 km^2. For most cells, maximum and minimum air temperature and precipitation are estimated from selected weather stations using a distance-weighted method (Bauer and Vaccaro, 1990). If the average daily air temperature for the cell was less than $0^{\circ}C$, then all of the precipitation for that day was assumed to be snow and was added to the snowpack. To estimate ET with the model for the Snively Basin site, the model was modified to accept actual air temperature and precipitation data collected at the site. This modification allows the model to be used to calculate ET and recharge for more site-specific areas.

The model used user-variable parameters described by Bauer and Vaccaro (1990). For the Snively Basin site model simulations, the soil type used was a silty loam and soil depth for the model was set at 0.6 m (consisting of four 0.15-m layers), 0.4 m deeper than the observed rooting depth. To compute plant transpiration, the model uses Blaney-Criddle crop-growth coefficients (U.S. Department of Agriculture, 1967) from growth curves for grasses. In the Blaney-Criddle formulation, the growing season for plant transpiration is considered to be from last frost in the spring to first frost in the fall.

EVALUATION OF EVAPOTRANSPIRATION

Energy-budgets, ET estimates, and water budgets provided a variety of information needed to evaluate ET at the grass and sage lysimeter, Snively Basin, Turnbull meadow and marsh, and Black Rock Valley sites. For energy-budget methods of estimating ET, energy budgets of net radiation, soil-heat flux, sensible-heat flux, and latent-heat flux were calculated from the collected data. From the latent-heat fluxes, which were estimated by the Bowen-ratio and Penman-Monteith methods, ET estimates were made. ET estimates made using the Bowen-ratio latent-heat fluxes represent Bowen-ratio ET. ET estimates made using the Penman-Monteith latent-heat fluxes represent Penman-Monteith ET. ET estimates made using weighing lysimeters or the deep-percolation model, which did use energy-budget fluxes, are termed, respectively, lysimeter ET and model ET.

Bowen-ratio and Penman-Monteith ET agreed well with each other for the Snively Basin, Turnbull meadow, and Black Rock Valley sites—squares of the correlation coefficient (r^2) were 0.97, 0.96, and 0.91, respectively, for the sites. These close agreements were primarily the result of using the Bowen-ratio method to calibrate the Penman-Monteith method for the canopy resistance—they were not independent methods or results. Bowen-ratio ET was only 41 percent of lysimeter ET for 6 weeks in April and May 1991 at the grass lysimeter site but it was 96 percent of lysimeter ET at the sage lysimeter site during 8 days in July 1992.

For the Snively Basin site, annual Penman-Monteith ET differed from annual model ET by 0.4 percent for 1991 and by 1.2 percent for 1992. However, on a daily, monthly, and seasonal basis, the differences between Penman-Monteith ET and model ET were usually greater, averaging 25.2 percent on a daily basis, 4.0 percent on a monthly basis, and 0.7 percent on a seasonal basis. The r^2 of the daily values of Penman-Monteith ET and model ET of 0.57 indicated considerable variability.

Water budgets calculated for the Snively Basin site and grass and sage lysimeter sites were similar. The budgets showed that 100 percent of the precipitation became ET in 1991 and about 91 to 98 percent became ET in 1992. A water budget for the Turnbull meadow site could not be calculated because soil moisture conditions, precipitation, and ET prior to May 1991 (when data collection commenced) could not be accurately determined (S. Tomlinson, U.S. Geological Survey, written commun., 1994). No water budgets could be calculated for the Turnbull marsh or Black Rock Valley sites because of insufficient data.

Energy Budgets

In an energy budget, net radiation equals the sum of soil-heat flux, sensible-heat flux, and latent-heat flux (eq. 1). The variability of net radiation and the other fluxes depended on many conditions such as type, height, and extent of vegetation, stage of plant growth, amount and density of cloud cover, rainfall, wind speed, season of the year, and soil-moisture content. Some plant canopies, such as forests, can also store large amounts of heat, which can be part of the energy budget. Canopy-heat storage for the grass and sagebrush sites was considered negligible because of the sparse nature or short height of the canopies.

Net radiation, usually the largest part of the energy budget at the eastern Washington study sites, varied depending on cloud cover and time of day (figs. 5-9). Net radiation curves were smooth for clear days, such as July 10 and 12, 1991 (fig. 7), October 3 and 4, 1991 (fig. 8), and May 7 and 10, 1992 (fig. 6). Net radiation measured near zero at sunrise and sunset on clear days, peaking around noon. The smoothness of net radiation graphs for clear days was also generally reflected in the other fluxes. Net radiation curves on partly-cloudy days, such as April 10-14, 1992 (fig. 5) and May 12 and 13, 1992 (fig. 6) were irregular due to clouds passing over the site. On completely cloudy days, such as April 9, 1992 (fig. 5), May 8, 1992 (fig. 6), and July 22-23, 1992 (fig. 9), net radiation and other fluxes were low and somewhat irregular, depending on the thickness of the cloud cover. Occasionally, irregularities in net radiation were not due to clouds. On July 11, 1991 a partial solar eclipse in mid-morning caused a dip in the net-radiation curve for an otherwise clear day (fig. 7).

During days of precipitation, such as April 9, 1992 (fig. 5), and July 23, 1992 (fig. 9), soil and atmospheric radiation produced little surface warming, so soil- and sensible-heat fluxes remained low. Most of the energy from net radiation was converted to latent-heat flux, which approached or slightly exceeded net radiation.

For periods when the top layer of soil and the air were extremely dry, such as October 1-7, 1991 (fig. 8), most net radiation became sensible-heat flux, and to a lesser extent, soil-heat flux. In this case, sensible-heat flux approached the net radiation while latent-heat flux approached zero.

Energy budgets showed other interesting relationships between soil, plants, and their environment. These relationships include processes such as frost and advection. May 7, 1992 (fig. 6) immediately followed 5 days of high latent-heat flux and ET (over 3 millimeters per day) at the Snively Basin site due to maximum daytime temperatures above 30°C. On May 10 and 11, 1992, the Snively Basin site showed similar net radiation and soil-heat flux; however, latent-heat flux on May 11 was only half of what it was on May 10. Air temperatures below freezing on the mornings of May 11, and May 12, 1992, might have stressed the grasses enough to affect their ability to transpire effectively. Afternoon high temperatures were about 18°C on both days. In another case, an unusual nighttime advection condition showed up as a spike of latent-heat flux (fig. 7) and ET. At the Turnbull meadow site on July 13, 1991, just after midnight, wind speed increased from 1.5 to 6 m/s, air temperatures rose from 18.6 to 24.8°C, and relative humidity dropped from 64 to 44 percent. A nearby thunderstorm may have advected warmer, drier air to the site because, an hour later, some rainfall was measured. The phenomenon was large-scale because it was also observed at the Turnbull marsh site. Other effects such as plant senescence, evaporation at night, and seasonal variation were shown by Tomlinson (1995).

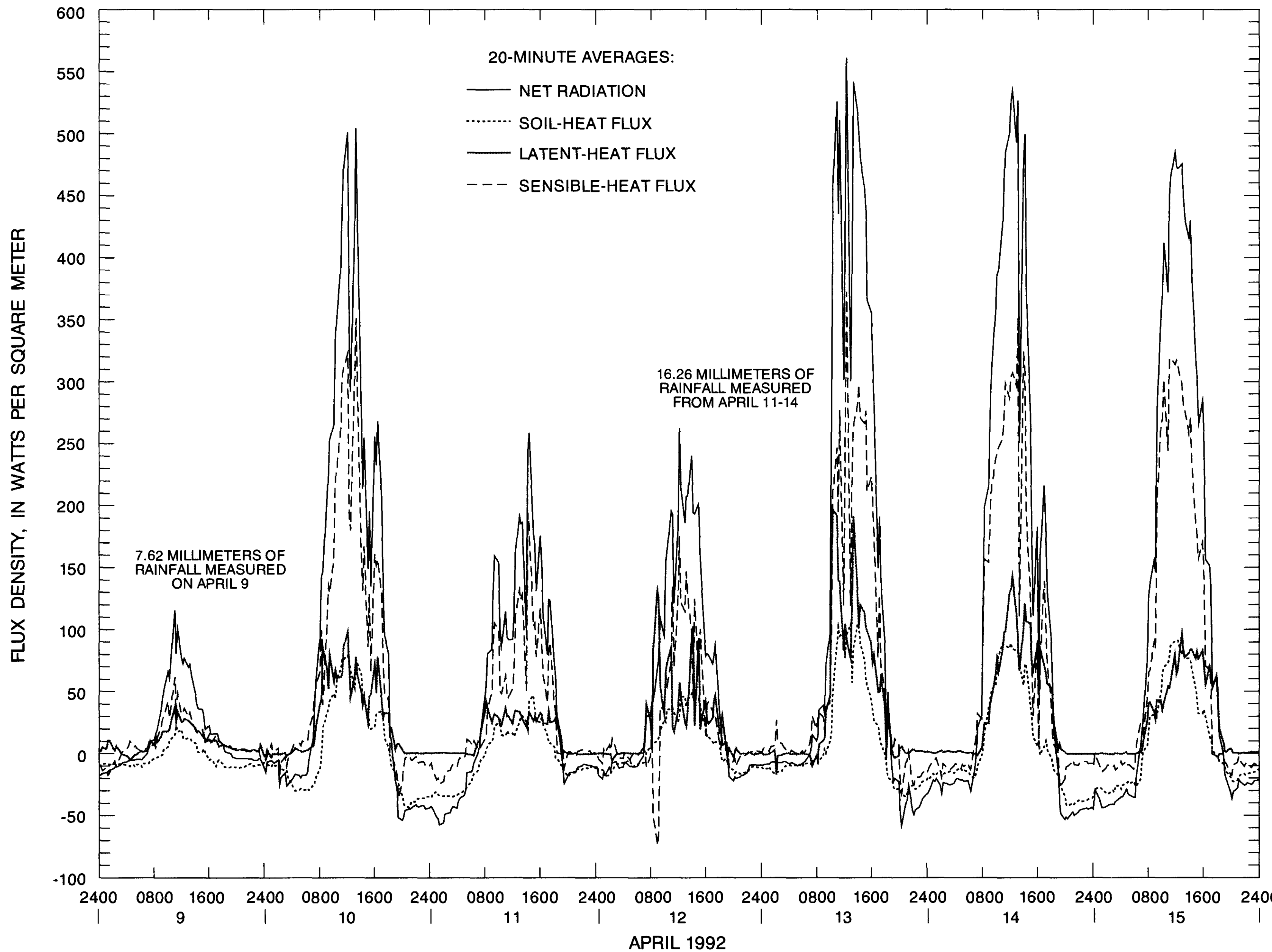

Figure 5.--Energy budget from the Bowen-ratio method at the Snively Basin site, April 9-15, 1992.

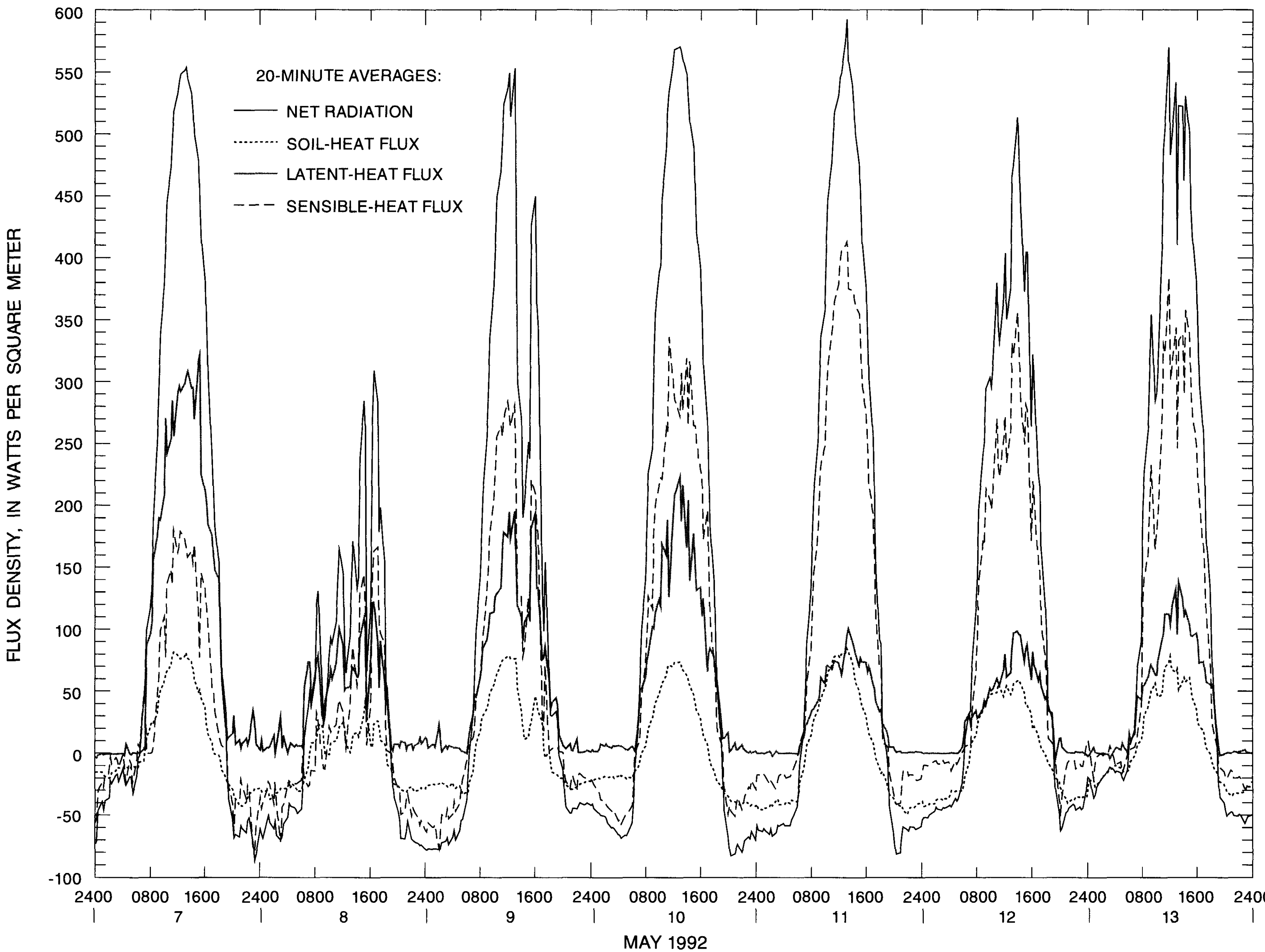

Figure 6.--Energy budget from the Bowen-ratio method at the Snively Basin site, May 7-13, 1992.

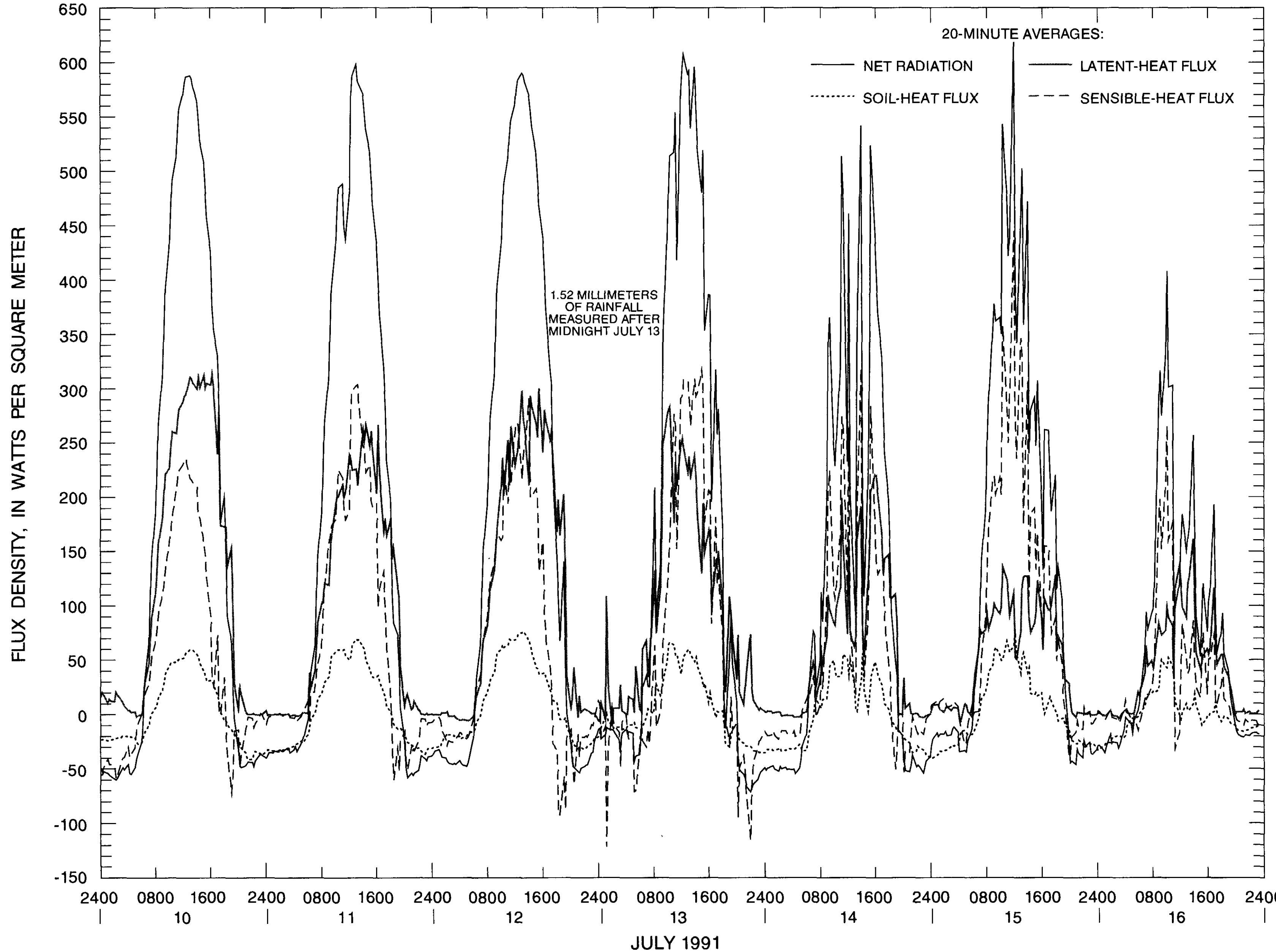

Figure 7.--Energy budget from the Bowen-ratio method at the Turnbull meadow site, July 10-16, 1991.

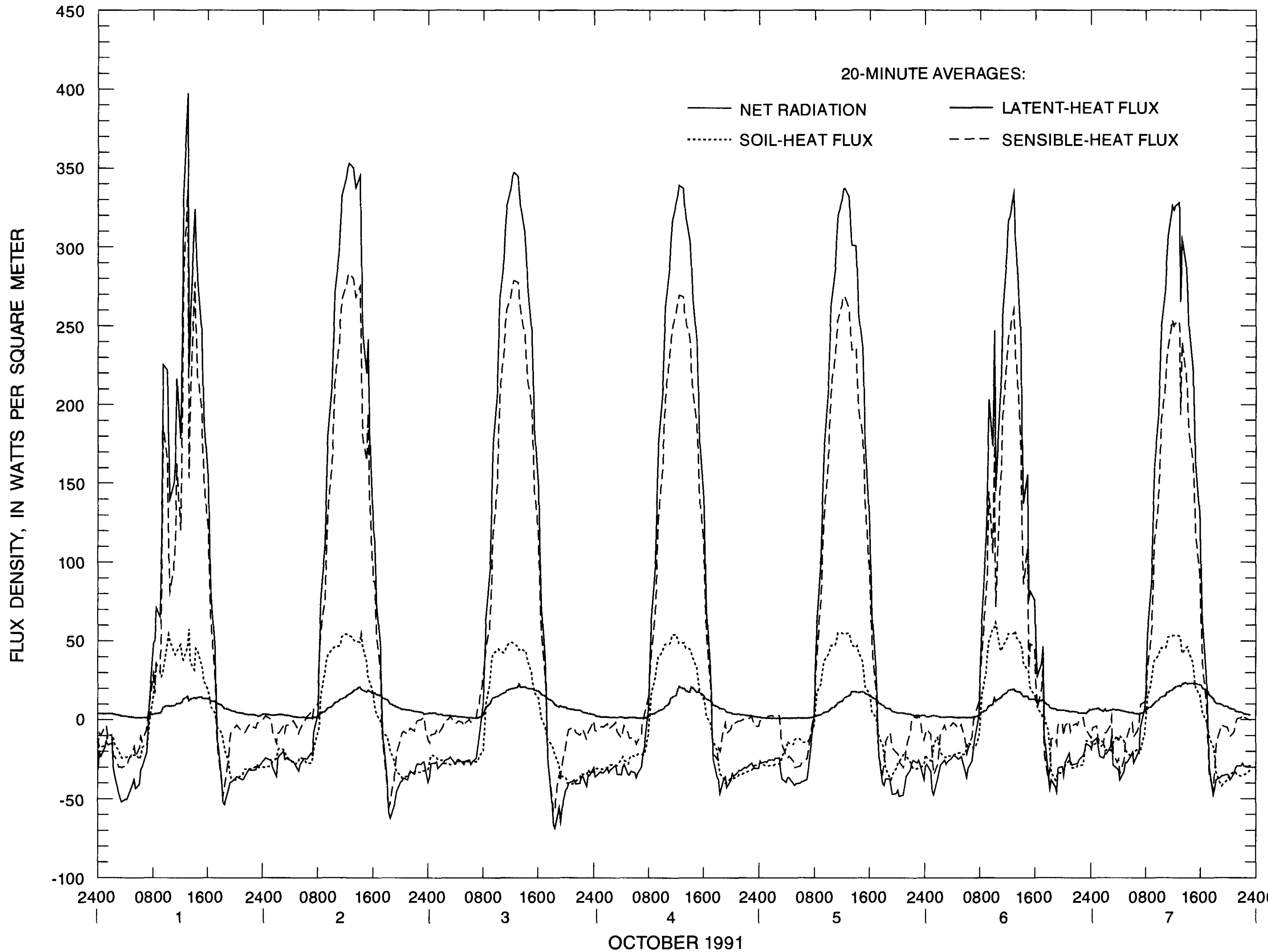

Figure 8.--Energy budget from the Penman-Monteith method at the Turnbull meadow site, October 1-7, 1991.

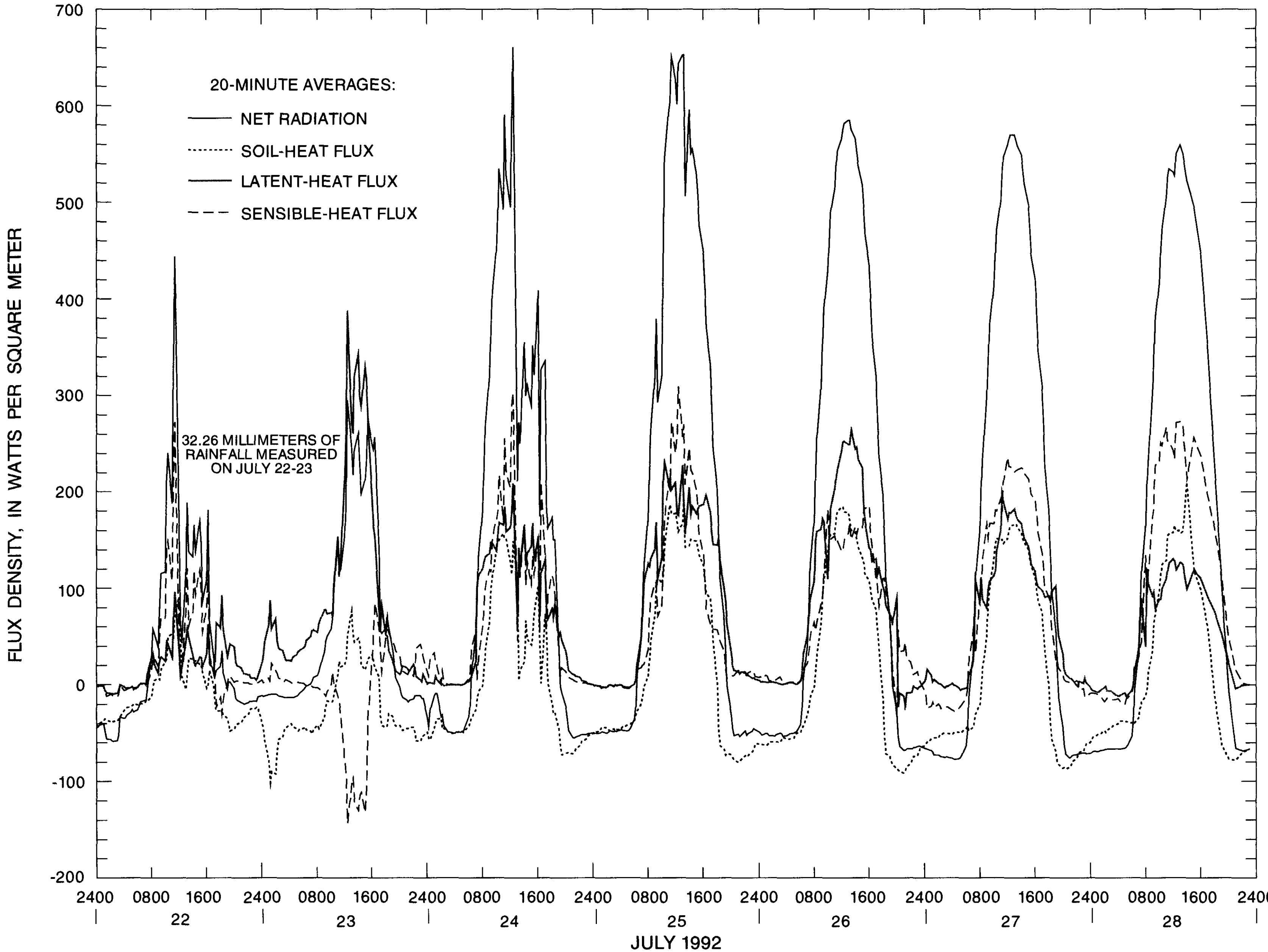

Figure 9.--Energy budget from the Bowen-ratio method at the Black Rock Valley site, July 22-28, 1992.

Evapotranspiration Estimates

ET estimates were made on the basis of data from energy-budget flux calculations, data from lysimeters at the grass and sage lysimeter sites, and results from the model. For the Snively Basin, Turnbull meadow, and Black Rock Valley 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 step (20 or 60 minutes) from about 8 a.m. to 5 p.m. were averaged for the day. Latent-heat flux and ET were recalculated with the average daily canopy resistance in the Penman-Monteith method for each time step. For these three sites, this procedure produced satisfactory daily estimates of Penman-Monteith ET, compared with daily estimates of Bowen-ratio ET. For example, at the Snively Basin site, latent-heat flux and ET estimated with the Penman-Monteith method for the period May 7 to May 13, 1992 were only 9 percent more than those estimated with the Bowen-ratio method. Comparison of the latent-heat fluxes made with the Bowen-ratio and Penman-Monteith methods show this similarity at the three sites (figs. 10-12). Other examples are shown by Tomlinson (1994) and Tomlinson (1995).

Grass and Sage Lysimeter Sites

Precipitation measured by the lysimeters at the grass and sage lysimeter sites agreed closely, as did ET for the two sites (table 2, figs. 13-14). Total ET from August 20, 1990 to September 30, 1992 at the grass lysimeter site (466 mm) agreed within 1 percent of the ET for the same period at the sage lysimeter site (469 mm). Total precipitation measured by the weighing lysimeters at the grass lysimeter site for this same period (478 mm) agreed within 1 percent of precipitation measured by lysimeters at the sage lysimeter site (470 mm). On a daily basis, ET values at both sites were close, with an r^2 of 0.93. This close agreement can be expected because the sites are only 450 mm apart.

Comparisons between Bowen-ratio ET and weighing-lysimeter ET for the grass and sage lysimeter sites were more variable. For the grass lysimeter site from April 2 to May 13, 1991, total ET estimated with the Bowen-ratio method was only 41 percent of the total ET measured by the lysimeters (table 3). On a daily basis, there was considerable variability; r^2 was 0.56. These differences might have been caused by instrument error, invalidation of assumptions in the Bowen-ratio method resulting from processes such as advection of air from unrepresentative areas, or conditions in the lysimeters not representing conditions in the larger area surrounding the site.

Although it may be possible that the lysimeters at the grass lysimeter site did not always represent true conditions at the site, subsequent investigations by the author in 1993 and 1994 at the site (S. Tomlinson, U.S. Geological Survey, written commun., 1994) suggest Bowen-ratio instrument problems were probably responsible for the large differences between the Bowen-ratio and weighing-lysimeter ET estimates. Worn o-ring seals may have allowed leakage of air into the cooled-mirror chamber of the DEW-10 system at the grass lysimeter site, which would reduce the measured vapor-pressure gradient, and thus the latent-heat flux and ET rate.

Without the weighing-lysimeter data for comparison, there would have been no indication that the Bowen-ratio vapor-pressure data were possibly erroneous. Measurements such as net radiation (two net radiometers were used), air temperature and air-temperature difference, soil temperature, and soil-heat flux (four soil-heat-flux transducers were used) all appeared reasonable. The vapor-pressure values collected by the DEW-10 at the grass lysimeter site appeared reasonable; however, the vapor-pressure gradients did not. The vapor-pressure gradients were extremely small, even during conditions when large gradients would have been expected, such as after rainfall. Subsequent studies at the grass lysimeter site failed to substantiate large differences between results from the weighing lysimeters and the Bowen-ratio method (S. Tomlinson, U.S. Geological Survey, written commun., 1994). Instrument error, possibly in the vapor-pressure measurements, was the likely reason for the unusually low Bowen-ratio ET estimates, compared with the lysimeter ET estimates.
(Text continued on p. 45.)

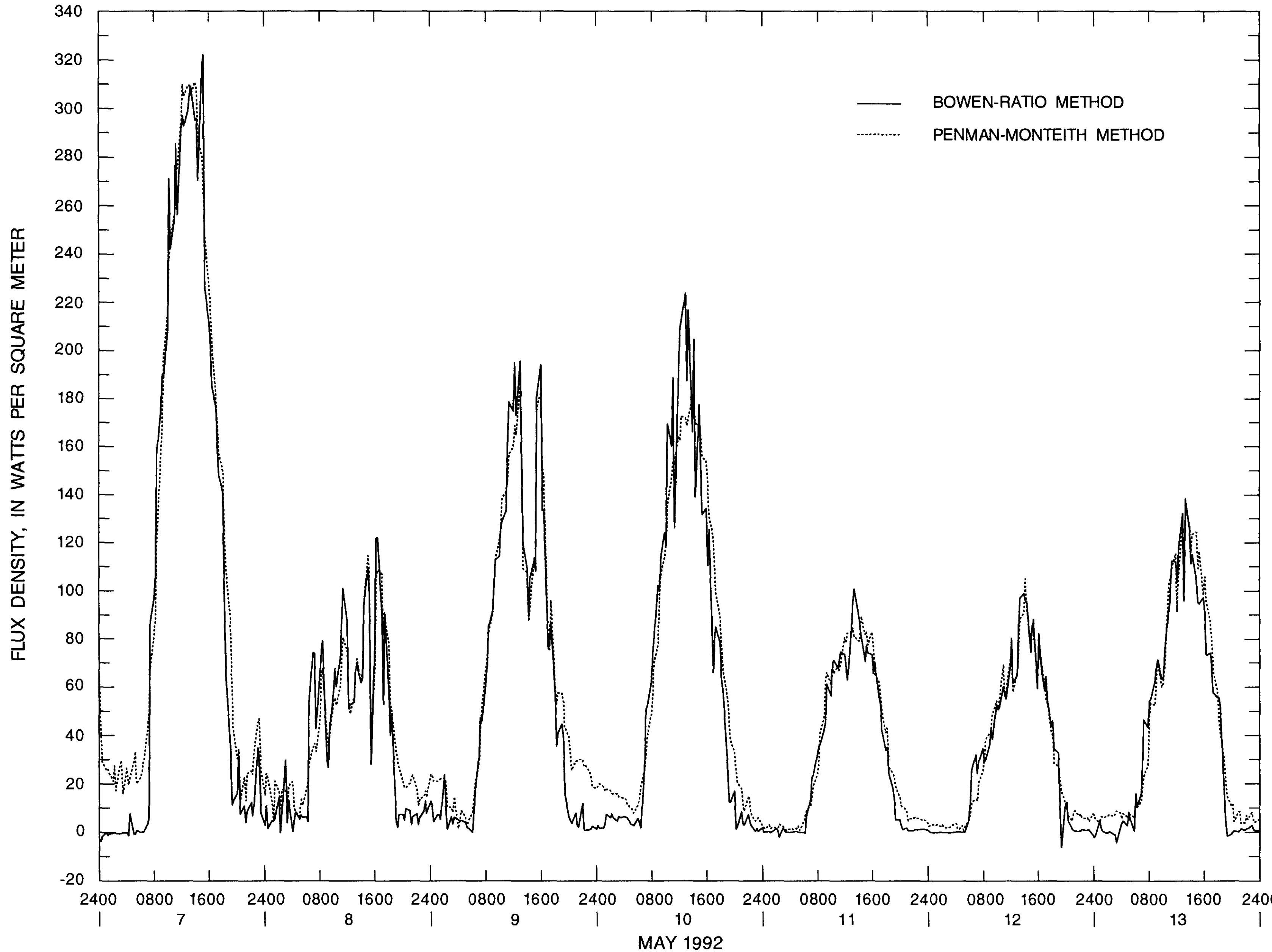

Figure 10.--Latent-heat flux from the Bowen-ratio and Penman-Monteith methods at the Snively Basin site, May 7-13, 1992.

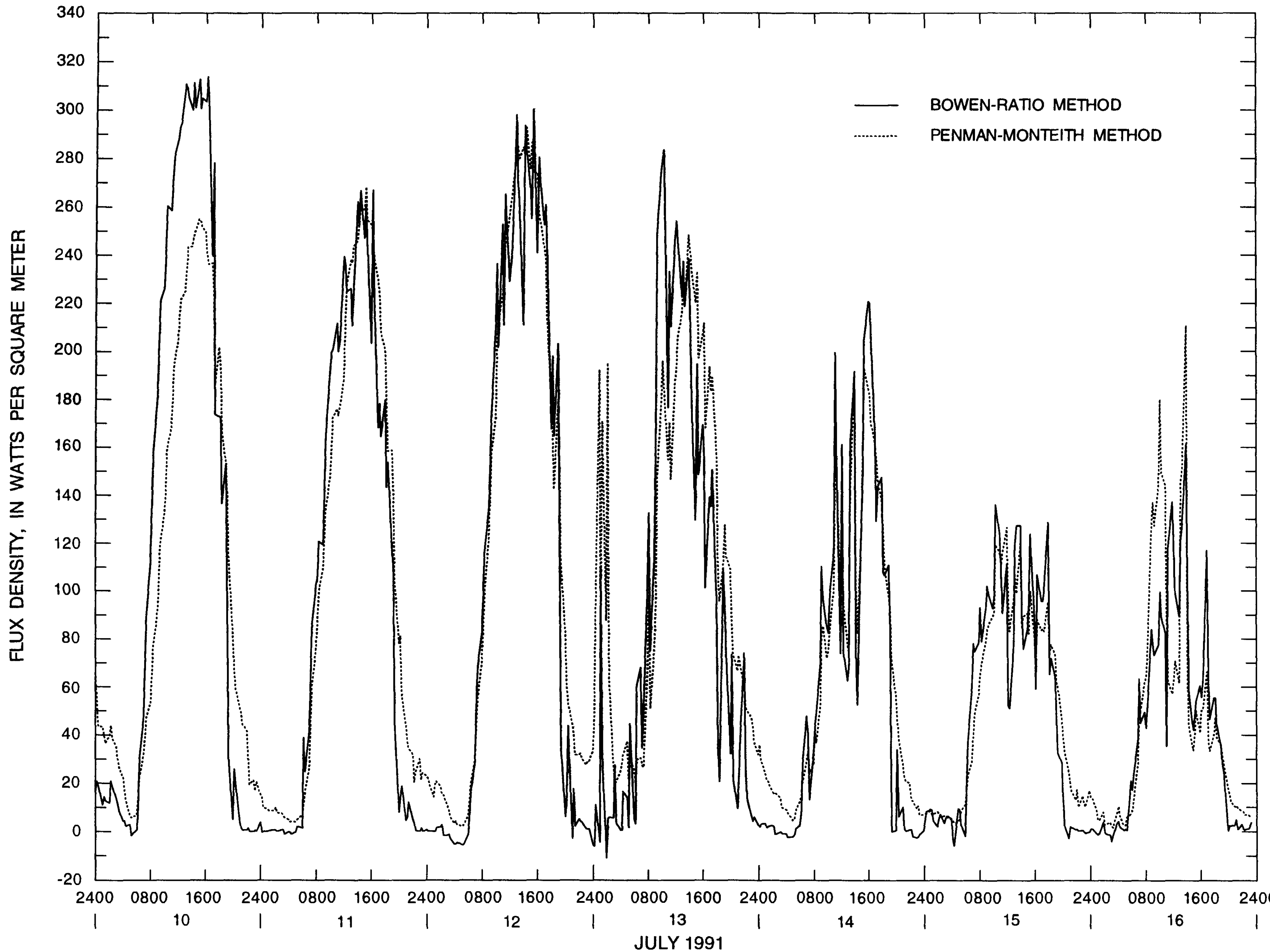

Figure 11.--Latent-heat flux from the Bowen-ratio and Penman-Monteith methods at theTurnbull meadow site, July 10-16, 1991.

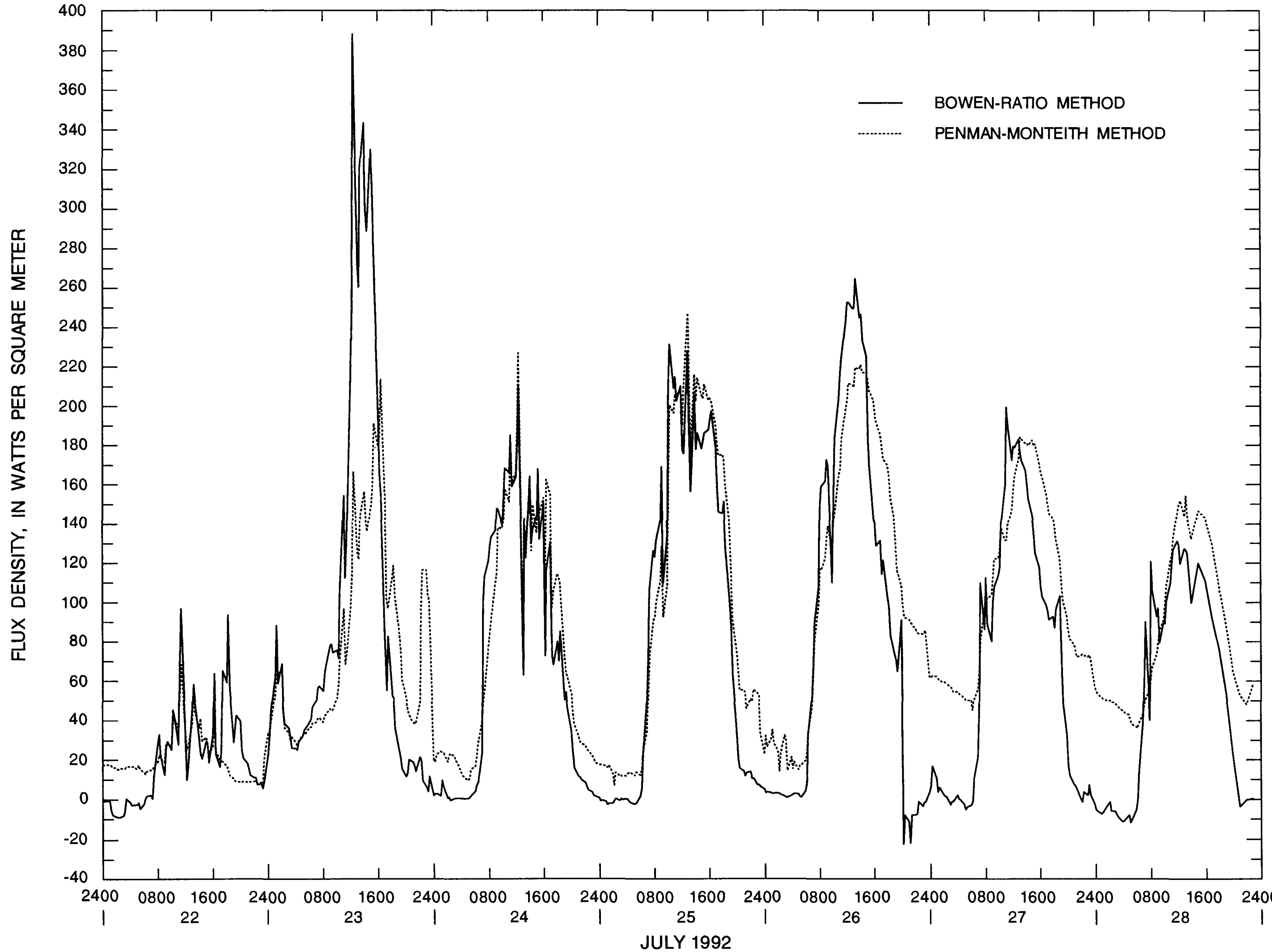

Figure 12.--Latent-heat flux from the Bowen-ratio and Penman-Monteith methods at the Black Rock Valley site, July 22-28, 1992.

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992*

[Precipitation and evapotranspiration estimates for the weighing lysimeters are based on data collected and provided by Battelle, Pacific Northwest Laboratories; mm, millimeters; PRG, average precipitation from two weighing lysimeters at grass lysimeter site; PRS, average precipitation from two weighing lysimeters at sage lysimeter site; ETG, average evapotranspiration from two weighing lysimeters at grass lysimeter site; ETS, average evapotranspiration from two weighing lysimeters at sage lysimeter site; TOT, monthly totals of daily precipitation and evapotranspiration; *, partially estimated]

	May 1990				June 1990				July 1990			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.00	0.00	0.57	0.56	0.00	0.00	1.80	1.69	0.14	0.06	0.22	0.16
2	0.00	0.00	0.56	0.64	0.00	0.00	0.75	0.81	0.23	0.36	0.24	0.28
3	0.00	0.00	0.45	0.64	0.24	0.24	0.64	0.66	0.00	0.00	0.22	0.12
4	0.00	0.00	0.49	0.58	0.00	0.00	0.50	0.53	0.00	0.00	0.12	0.22
5	0.00	0.00	0.39	0.50	0.00	0.00	0.30	0.30	0.00	0.00	0.02	0.14
6	0.00	0.00	0.26	0.33	3.20	3.14	1.25	1.18	0.00	0.00	0.12	0.13
7	0.00	0.00	0.30	0.16	0.00	0.00	1.38	1.47	0.00	0.00	0.13	0.20
8	0.00	0.00	0.16	0.33	0.00	0.00	0.41	0.33	0.00	0.00	0.22	-0.24
9	0.00	0.00	0.23	0.33	0.00	0.00	0.46	0.45	0.00	0.00	0.13	0.31
10	0.00	0.00	0.32	0.27	0.27	0.23	0.58	0.70	0.00	0.00	0.13	0.31
11	0.30	0.26	0.30	0.36	0.00	0.00	0.25	0.30	0.00	0.00	0.14	0.29
12	0.72	0.45	0.47	0.39	0.00	0.00	0.20	0.19	0.00	0.00	0.13	0.33
13	0.00	0.00	0.52	0.39	0.00	0.00	0.19	0.25	0.00	0.00	0.20	0.23
14	0.00	0.00	0.11	0.10	0.00	0.00	0.35	0.39	0.00	0.00	0.13	0.26
15	0.00	0.00	0.24	0.26	0.00	0.00	0.17	0.30	0.00	0.00	0.13	0.26
16	0.00	0.00	0.24	0.36	0.00	0.00	0.23	0.35	0.00	0.00	0.12	0.22
17	0.00	0.00	0.09	0.20	0.00	0.00	0.17	0.30	0.00	0.00	0.12	0.14
18	0.00	0.00	0.17	0.24	0.00	0.00	0.17	0.31	0.00	0.00	0.13	0.21
19	0.01	0.02	0.18	0.28	0.00	0.00	0.16	0.22	0.00	0.00	0.08	0.18
20	0.35	0.42	0.40	0.50	0.00	0.00	0.25	0.37	0.00	0.00	0.11	0.21
21	0.59	0.52	0.22	0.23	0.00	0.00	0.23	0.36	0.00	0.00	0.08	0.20
22	2.90	2.73	0.75	0.66	0.00	0.00	0.02	0.05	0.00	0.00	0.12	0.16
23	7.39	7.35	1.37	1.21	0.00	0.00	0.20	0.37	0.00	0.00	0.03	0.10
24	0.00	0.00	2.08	2.01	0.00	0.00	0.24	0.39	0.49	0.44	0.45	0.28
25	0.00	0.00	1.08	1.03	0.00	0.00	0.19	0.26	1.52	1.60	1.08	1.01
26	0.00	0.00	0.53	0.62	0.00	0.00	0.14	0.20	0.12	0.17	0.56	0.61
27	0.64	0.73	0.64	0.66	0.00	0.00	0.28	0.16	0.00	0.00	0.16	0.19
28	1.56	1.43	0.59	0.56	0.00	0.00	0.14	0.26	0.00	0.00	0.14	0.16
29	0.05	0.09	1.28	1.46	0.00	0.00	0.15	0.23	0.00	0.00	0.11	0.29
30	1.46	1.63	0.78	0.68	0.00	0.00	0.18	0.29	0.51	0.32	0.17	0.19
31	3.15	2.80	1.35	1.47					1.71	1.23	1.81	1.47
TOT	19.12	18.43	17.12	18.01	3.71	3.61	11.98	13.67	4.72	4.18	7.55	9.10

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	August 1990				September 1990				October 1990			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.00	0.00	0.32	0.21	0.00	0.00	0.38	0.42	0.00	0.00	0.02	0.00
2	0.00	0.00	0.14	0.16	0.00	0.00	0.37	0.41	0.00	0.00	0.13	0.00
3	0.00	0.00	0.12	0.16	0.00	0.00	0.37	0.39	0.00	0.00	0.01	0.00
4	0.00	0.00	0.14	0.20	0.00	0.00	0.37	0.44	0.00	0.00	0.10	0.19
5	0.00	0.00	0.08	0.23	0.00	0.00	0.30	0.40	0.00	0.00	0.12	0.00
6	0.00	0.00	0.10	0.23	0.00	0.00	0.26	0.32	0.00	0.00	0.16	0.00
7	0.00	0.00	0.05	0.12	0.00	0.00	0.15	0.13	0.00	0.00	0.14	0.00
8	0.00	0.00	0.02	0.15	0.00	0.00	0.30	0.31	0.00	0.00	0.11	0.00
9	0.00	0.00	0.04	0.11	0.00	0.00	0.27	0.31	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.06	0.00	0.00	0.25	0.26	0.00	0.00	0.09	0.08
11	0.00	0.00	0.08	0.09	0.00	0.00	0.18*	0.31*	0.00	0.00	0.08	0.00
12	0.00	0.00	0.07	0.18	0.00	0.00	0.18	0.12	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.16	0.00	0.00	0.20	0.15	0.00	0.00	0.12	0.00
14	0.00	0.00	0.18	0.11	0.00	0.00	0.22	0.18	1.90	1.91	0.91	0.72
15	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.54	0.53
16	0.00	0.00	0.08	0.09	0.00	0.00	0.28	0.15	0.00	0.00	0.33	0.15
17	0.00	0.00	0.02	0.00	0.00	0.00	0.09	0.13	0.00	0.00	0.13	0.00
18	0.00	0.00	0.06	0.00	0.00	0.00	0.14	0.13	4.50	4.55	0.97	0.96
19	0.51	0.35	0.29	0.08	0.00	0.00	0.18	0.16	0.00	0.00	1.20	0.99
20	0.14	0.12	0.19	0.07	0.00	0.00	0.21	0.18	0.24	0.25	0.43	0.32
21	20.06	20.37	1.32	1.38	0.00	0.00	0.10	0.08	0.61	0.71	0.75	0.70
22	0.00	0.00	2.67	2.53	0.00	0.00	0.14	0.11	0.00	0.17	0.46	0.63
23	0.00	0.00	1.55	1.28	0.00	0.00	0.16	0.13	0.00	0.00	0.24	0.19
24	0.00	0.00	1.03	0.96	0.00	0.00	0.08	0.13	0.00	0.00	0.17	0.11
25	0.00	0.00	0.88	0.86	0.00	0.00	0.10	0.14	1.89	1.83	0.39	0.17
26	0.00	0.00	0.66	0.61	0.00	0.00	0.14	0.07	0.19	0.25	1.12	1.14
27	0.00	0.00	0.62	0.64	0.00	0.00	0.13	0.15	0.08	0.00	0.46	0.32
28	0.00	0.00	0.49	0.58	0.0.0	0.00	0.15	0.13	0.00	0.00	0.31	0.39
29	1.80	1.53	1.31	1.07	0.00	0.00	0.17	0.14	1.80	1.86	0.21	0.15
30	0.00	0.00	1.06	0.97	0.00	0.00	0.12	0.06	13.22	13.06	0.23	0.17
31	0.00	0.00	0.44	0.51					0.24	0.24	1.66	1.69
TOT	22.51	22.37	14.01	13.80	0.00	0.00	6.06	6.04	24.67	24.83	11.59	9.60

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	November 1990				December 1990				January 1991			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.00	0.00	1.12	0.94	0.29	0.28	0.27	0.28	0.00	0.00	0.12	0.22
2	0.00	0.00	0.55	0.31	0.00	0.00	0.29	0.09	0.00	0.00	0.66	0.29
3	0.00	0.00	0.42	0.34	0.00	0.00	0.09	0.22	0.00	0.00	0.19	0.23
4	0.12	0.17	0.63	0.69	0.00	0.00	0.14	0.23	0.00	0.00	0.31	0.01
5	0.00	0.00	0.56	0.40	0.00	0.00	0.14	0.07	0.16	0.15	0.11	0.00
6	0.00	0.00	0.40	0.27	0.00	0.00	0.09	0.00	1.70	1.72	0.20	0.15
7	0.00	0.00	0.32	0.37	0.26	0.39	0.18	0.19	2.18	2.23	0.00	0.07
8	0.00	0.00	0.30	0.23	0.11	0.21	0.18	0.18	0.14	0.12	0.07	0.11
9	0.00	0.00	0.43	0.69	4.09	4.14	0.08	0.02	2.68	3.03	0.09	0.10
10	0.00	0.00	0.40	0.61	7.77	7.70	0.18	0.28	3.90	3.94	0.14	0.18
11	0.00	0.00	0.14	0.12	0.00	0.00	0.88	0.74	2.19	2.21	0.20	0.57
12	0.00	0.00	0.24	0.15	0.00	0.00	0.24	0.07	1.31	2.36	2.88	4.06
13	0.00	0.00	0.33	0.39	0.00	0.00	0.13	0.03	0.00	0.00	1.78	1.75
14	0.00	0.00	0.32	0.27	0.00	0.00	0.24	0.11	0.00	0.00	1.23	1.41
15	0.00	0.00	0.23	0.17	0.00	0.00	0.19	0.09	0.00	0.00	1.01	1.29
16	0.00	0.00	0.22	0.01	0.00	0.00	0.24	0.23	0.58	0.47	0.20	0.08
17	0.06	0.10	0.16	0.08	0.00	0.00	0.82	0.86	0.00	0.00	0.24	0.31
18	0.02	0.01	0.26	0.21	2.84	3.03	0.77	0.75	0.00	0.00	0.08	0.01
19	0.00	0.00	0.18	0.00	4.01	4.65	0.59	0.61	0.00	0.00	0.51	0.38
20	0.00	0.00	0.22	0.15	0.00	0.00	0.47	0.12	0.00	0.00	0.33	0.25
21	0.10	0.12	0.21	0.01	0.00	0.00	0.23	0.00	0.00	0.00	0.24	0.11
22	0.16	0.11	0.34	0.71	0.00	0.00	0.11	0.00	0.00	0.00	0.21	0.12
23	0.25	0.23	0.46	0.52	0.00	0.00	0.25	0.00	0.00	0.00	0.11	0.07
24	0.68	0.60	0.38	0.59	0.00	0.00	0.23	0.00	0.00	0.00	0.31	0.23
25	0.62	0.60	0.88	0.77	0.00	0.00	0.11	0.03	0.00	0.00	0.31	0.15
26	0.00	0.00	0.31	0.00	0.00	0.00	0.13	0.05	0.08	0.09	0.08	0.00
27	0.00	0.00	0.30	0.23	0.00	0.00	1.34	1.42	0.00	0.00	0.14	0.11
28	0.00	0.00	0.18	0.00	6.34	7.47	0.26	0.37	0.00	0.00	0.31	0.28
29	0.86	1.08	0.54	0.75	0.00	0.00	0.34	0.25	0.00	0.00	0.11	0.00
30	0.00	0.00	0.43	0.25	2.36	2.39	0.18	0.11	0.00	0.00	0.10	0.02
31					0.52	0.32	0.69	0.69	0.21	0.18	0.23	0.29
TOT	2.81	3.02	11.46	10.23	28.59	30.58	10.08	8.09	15.13	16.50	12.50	12.85

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

Day	February 1991 PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	March 1991 PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	April 1991 PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.12	0.07	0.16	0.24	0.13	0.15	0.15	0.00	0.00	0.00	1.27	1.61
2	1.09	1.01	0.50	0.60	6.73	6.87	1.12	0.78	0.22	0.27	1.10	1.42
3	0.43	0.39	0.64	0.86	5.04	5.08	2.22	2.45	0.60	0.62	0.70	0.76
4	3.66	3.57	0.42	0.70	2.17	1.92	1.00	0.88	6.13	5.93	1.69	1.79
5	1.39	1.50	1.45	1.78	0.14	0.02	1.74	1.98	0.00	0.00	2.66	2.86
6	0.14	0.09	0.62	0.71	0.00	0.00	1.18	1.18	0.00	0.00	1.37	1.35
7	0.02	0.08	0.47	0.57	0.00	0.00	1.00	1.16	0.00	0.00	1.13	1.20
8	0.00	0.00	0.47	0.54	0.00	0.00	0.82	0.92	2.41	2.48	0.88	0.90
9	0.00	0.00	0.34	0.42	0.18	0.13	0.54	0.59	0.36	0.31	2.17	2.36
10	0.23	0.31	0.28	0.36	0.00	0.05	0.91	1.13	0.00	0.00	1.25	1.16
11	0.12	0.10	0.19	0.17	1.36	1.20	0.58	0.56	0.00	0.00	1.43	1.37
12	2.32	1.71	0.62	0.58	0.93	0.77	1.03	1.08	0.00	0.00	1.24	1.14
13	2.14	2.12	0.34	0.36	0.00	0.00	0.98	1.13	0.00	0.00	1.23	1.15
14	0.26	0.22	0.70	0.76	0.00	0.00	0.74	0.73	0.53	0.60	0.93	0.90
15	0.00	0.00	0.27	0.43	0.23	0.24	0.93	1.05	5.20	5.15	1.00	0.97
16	0.00	0.00	1.17	1.24	0.00	0.00	0.67	0.74	0.09	0.03	2.19	2.15
17	0.00	0.00	1.06	1.07	0.00	0.00	0.67	0.79	0.00	0.00	1.54	1.47
18	0.00	0.00	0.20	0.12	0.19	0.11	0.59	0.61	0.00	0.00	1.42	1.30
19	0.00	0.00	0.95	1.04	0.75	0.42	0.50	0.44	0.00	0.00	1.25	1.13
20	0.74	0.70	1.16	1.43	0.04	0.05	1.25	1.10	0.00	0.00	1.22	1.07
21	0.00	0.00	0.50	0.55	0.13	0.15	0.59	0.63	0.00	0.00	1.16	1.11
22	0.00	0.00	0.62	0.67	0.00	0.00	0.60	0.75	0.00	0.00	1.04	0.90
23	0.00	0.00	0.60	0.66	0.06	0.06	0.42	0.43	0.22	0.15	0.77	0.66
24	0.00	0.00	0.57	0.62	13.37	12.69	0.50	0.60	0.11	0.12	0.83	0.79
25	0.00	0.00	0.42	0.54	4.47	4.25	0.50	0.38	0.00	0.00	0.43	0.33
26	0.00	0.00	0.51	0.62	0.00	0.00	2.38	2.67	0.00	0.00	0.65	0.45
27	0.00	0.00	0.46	0.52	0.00	0.00	1.78	1.87	0.00	0.00	0.46	0.42
28	0.00	0.00	0.50	0.52	0.00	0.00	1.26	1.42	0.00	0.00	0.47	0.36
29					0.00	0.00	1.33	1.36	0.00	0.00	0.58	0.59
30					0.00	0.00	1.23	1.34	0.00	0.00	0.58	0.51
31					0.00	0.00	1.11	1.38				
TOT	12.66	11.87	16.19	18.68	35.92	34.16	30.32	32.13	15.87	15.66	34.64	34.18

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	May 1991				June 1991				July 1991			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.16	0.07	0.51	0.42	0.00	0.00	0.27	0.42	0.00	0.00	0.79	0.98
2	0.00	0.00	0.61	0.59	0.00	0.00	0.22	0.35	0.00	0.00	0.86	1.03
3	0.35	0.19	0.43	0.38	0.00	0.00	0.27	0.30	0.00	0.00	0.93	0.97
4	0.03	0.04	0.78	0.66	0.00	0.00	0.20	0.18	0.00	0.00	0.77	0.94
5	0.18	0.13	0.45	0.36	0.00	0.00	0.35	0.26	0.00	0.00	0.70	0.67
6	0.00	0.00	0.29	0.27	9.62	9.46	2.85	2.94	0.00	0.00	0.58	0.57
7	1.80	1.68	0.35	0.23	4.12	4.11	1.62	1.53	0.00	0.00	0.62	0.56
8	3.14	3.19	2.32	2.40	0.33	0.35	1.09	1.15	0.00	0.00	0.62	0.66
9	0.00	0.00	0.81	0.63	0.00	0.00	0.91	1.00	0.00	0.00	0.52	0.53
10	0.00	0.00	0.60	0.48	0.00	0.00	0.83	0.96	0.00	0.00	0.54	0.45
11	0.14	0.13	0.52	0.47	0.00	0.00	0.61	0.76	0.00	0.00	0.50	0.45
12	0.36	0.37	0.67	0.78	0.00	0.00	0.44	0.45	0.00	0.00	0.55	0.46
13	0.00	0.00	0.44	0.39	0.57	0.51	0.67	0.61	0.60	0.62	0.82	0.90
14	0.00	0.00	0.54	0.58	0.00	0.00	0.62	0.63	0.00	0.00	0.46	0.38
15	0.00	0.00	0.41	0.39	0.05	0.03	0.41	0.40	0.00	0.00	0.18	0.07
16	4.18	3.96	0.58	0.69	0.08	0.10	0.43	0.48	1.24	1.20	0.97	0.87
17	3.46	3.35	1.25	1.37	0.43	0.22	0.81	0.62	0.00	0.00	0.50	0.43
18	0.58	0.53	1.47	1.41	0.00	0.00	0.30	0.34	0.00	0.00	0.47	0.30
19	0.00	0.00	0.63	0.48	5.77	5.14	0.34	0.33	0.00	0.00	0.38	0.36
20	0.00	0.00	0.97	0.86	12.70	11.98	2.77	2.65	0.00	0.00	0.41	0.33
21	0.00	0.00	0.92	0.97	1.16	1.34	1.47	1.69	0.00	0.00	0.36	0.34
22	0.00	0.00	0.78	0.70	0.38	0.26	1.59	1.53	0.00	0.00	0.39	0.33
23	0.00	0.00	0.38	0.43	0.00	0.00	1.59	1.53	0.00	0.00	0.40	0.33
24	0.00	0.00	0.51	0.48	0.00	0.00	1.13	1.10	0.00	0.00	0.30	0.29
25	0.00	0.00	0.32	0.28	0.00	0.00	1.10	1.26	0.00	0.00	0.23	0.21
26	0.00	0.00	0.34	0.39	0.00	0.00	0.88	1.06	0.00	0.00	0.28	0.22
27	0.00	0.00	0.33	0.36	0.00	0.00	0.94	1.12	0.00	0.00	0.25	0.25
28	0.00	0.00	0.27	0.40	0.10	0.12	0.78	1.00	0.00	0.00	0.29	0.26
29	0.00	0.00	0.20	0.09	0.11	0.30	0.48	0.76	0.00	0.00	0.26	0.24
30	0.00	0.00	0.24	0.37	0.00	0.00	0.92	0.95	0.00	0.00	0.26	0.21
31	0.00	0.00	0.24	0.33					0.40	0.37	0.37	0.34
TOT	14.38	13.64	19.16	18.64	35.42	33.92	26.89	28.36	2.24	2.19	15.56	14.93

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	August 1991				September 1991				October 1991			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.34	0.25	0.80	0.66	0.00	0.00	0.07	0.08	0.00	0.00	0.10	0.06
2	0.00	0.00	0.29	0.27	0.00	0.00	0.10	0.07	0.00	0.00	0.12	0.06
3	0.00	0.00	0.26	0.28	0.00	0.00	0.11	0.09	0.00	0.00	0.05	0.01
4	0.00	0.00	0.22	0.21	0.00	0.00	0.06	0.07	0.00	0.00	0.07	0.00
5	0.00	0.00	0.11	0.12	0.00	0.00	0.11	0.12	0.00	0.00	0.09	0.00
6	1.23	1.42	0.45	0.47	0.00	0.00	0.00	0.06	0.00	0.00	0.03	0.00
7	0.00	0.00	0.81	0.91	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00
8	0.00	0.00	0.30	0.33	0.00	0.00	0.03	0.00	0.00	0.00	0.05	0.00
9	0.00	0.00	0.17	0.14	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.19	0.16	0.00	0.00	0.07	0.09	0.00	0.00	0.05	0.03
11	0.00	0.00	0.14	0.10	0.00	0.00	0.06	0.07	0.00	0.00	0.03	0.00
12	0.00	0.00	0.14	0.18	0.00	0.00	0.06	0.07	0.00	0.00	0.09	0.12
13	0.00	0.00	0.13	0.14	0.15	0.15	0.15	0.17	0.00	0.00	0.02	0.00
14	0.00	0.00	0.11	0.13	0.00	0.00	0.10	0.03	0.00	0.00	0.04	0.00
15	0.00	0.00	0.16	0.22	0.00	0.00	0.07	0.08	0.00	0.00	0.04	0.00
16	0.00	0.00	0.13	0.22	0.00	0.00	0.05	0.02	0.00	0.00	0.00	0.00
17	0.00	0.00	0.14	0.20	0.00	0.00	0.04	0.05	0.00	0.00	0.14	0.00
18	0.00	0.00	0.13	0.17	0.00	0.00	0.06	0.07	0.00	0.00	0.04	0.00
19	0.00	0.00	0.18	0.38	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.00
20	0.00	0.00	0.17	0.20	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.13	0.17	0.00	0.00	0.09	0.02	0.00	0.00	0.00	0.00
22	0.00	0.00	0.13	0.15	0.00	0.00	0.08	0.00	2.05	2.52	0.17	0.00
23	0.00	0.00	0.12	0.20	0.00	0.00	0.01	0.00	0.33	0.04	1.12	0.95
24	0.00	0.00	0.09	0.09	0.00	0.00	0.01	0.09	1.77	2.25	1.20	1.24
25	0.00	0.00	0.13	0.07	0.00	0.00	0.00	0.00	5.25	5.50	0.40	0.32
26	0.00	0.00	0.11	0.03	0.00	0.00	0.02	0.07	2.39	2.47	1.06	1.14
27	0.00	0.00	0.01	0.00	0.00	0.00	0.04	0.01	0.04	0.09	0.71	0.64
28	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.07	4.08	4.50	0.60	0.30
29	0.00	0.00	0.12	0.05	0.00	0.00	0.10	0.09	0.92	0.63	1.13	0.91
30	0.00	0.00	0.14	0.22	0.00	0.00	0.03	0.04	0.00	0.00	0.82	0.67
31	0.00	0.00	0.01	0.04					5.70	5.94	0.15	0.05
TOT	1.57	1.67	6.04	6.41	0.15	0.15	1.82	1.54	22.53	23.94	8.33	6.50

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	November 1991				December 1991				January 1992			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	1.04	1.14	1.12	0.94	0.00	0.00	0.93	0.96	0.15	0.13	0.16	0.15
2	0.00	0.00	0.55	0.31	0.00	0.00	0.90	1.07	1.75	1.74	0.42	0.59
3	0.11	0.11	0.42	0.34	0.00	0.00	0.44	0.60	3.90	3.79	0.22	0.17
4	4.84	4.79	0.63	0.69	0.00	0.00	0.75	0.94	0.26	0.37	0.53	0.71
5	5.81	5.83	0.56	0.40	5.87	5.43	1.03	0.96	6.31	6.46	0.15	0.18
6	0.22	0.24	0.40	0.27	2.79	2.67	0.71	0.84	0.00	0.00	0.45	0.61
7	0.27	0.29	0.32	0.37	0.00	0.00	1.29	1.20	0.00	0.00	0.64	0.50
8	0.52	0.49	0.30	0.23	0.00	0.00	1.39	1.45	0.00	0.00	0.26	0.23
9	1.02	1.04	0.43	0.69	0.00	0.00	1.06	1.16	0.00	0.00	0.24	0.21
10	0.09	0.16	0.40	0.61	0.00	0.00	0.48	0.32	0.68	0.81	0.06	0.06
11	0.13	0.10	0.14	0.12	0.00	0.00	0.87	0.86	0.00	0.00	1.12	1.33
12	0.00	0.01	0.24	0.15	0.00	0.00	0.86	0.95	0.00	0.00	0.24	0.12
13	0.49	0.43	0.33	0.39	0.00	0.00	0.35	0.07	0.00	0.00	0.18	0.16
14	0.00	0.00	0.32	0.27	0.00	0.00	0.33	0.18	0.00	0.00	0.09	0.15
15	0.00	0.00	0.23	0.17	0.00	0.00	0.21	0.01	0.00	0.00	0.06	0.05
16	8.59	8.80	0.22	0.01	0.00	0.00	0.12	0.00	4.40	4.24	0.23	0.26
17	0.09	0.08	0.16	0.08	0.13	0.22	0.26	0.25	0.00	0.00	0.21	0.25
18	0.15	0.18	0.26	0.21	2.23	2.27	0.18	0.20	0.00	0.00	0.24	0.19
19	4.89	4.90	0.18	0.00	0.00	0.00	0.22	0.18	0.00	0.00	0.28	0.30
20	0.00	0.00	0.22	0.15	0.00	0.00	0.07	0.00	0.00	0.00	0.30	0.27
21	0.00	0.00	0.21	0.01	3.53	3.46	0.02	0.00	0.00	0.00	0.77	0.91
22	0.00	0.00	0.34	0.71	2.22	2.12	0.18	0.32	0.14	0.11	0.29	0.26
23	0.81	0.79	0.46	0.52	0.00	0.00	0.12	0.20	0.58	0.72	0.85	1.17
24	5.54	5.43	0.38	0.59	0.82	0.83	0.08	0.16	0.00	0.02	0.61	0.99
25	1.85	1.79	0.88	0.77	0.00	0.00	0.27	0.36	0.02	0.00	0.88	0.96
26	10.65	10.64	0.31	0.00	0.00	0.00	0.19	0.19	0.15	0.17	0.20	0.12
27	0.00	0.00	0.30	0.23	0.00	0.00	0.21	0.24	3.82	3.87	0.05	0.04
28	6.92	6.96	0.18	0.00	0.21	0.21	0.18	0.18	4.33	4.19	1.82	2.02
29	0.00	0.00	0.54	0.75	0.15	0.16	0.28	0.34	0.17	0.19	1.21	1.35
30	0.00	0.00	0.43	0.25	0.11	0.10	0.20	0.19	0.00	0.00	0.37	0.41
31					0.04	0.05	0.14	0.21	0.00	0.00	0.66	0.74
TOT	54.03	54.20	19.19	19.49	18.10	17.52	14.32	14.59	26.66	26.81	13.79	15.46

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	February 1992				March 1992				April 1992			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.00	0.00	0.87	1.02	0.37	0.35	0.31	0.36	0.00	0.00	1.53	1.83
2	0.00	0.00	0.55	0.54	0.15	0.18	0.46	0.40	0.00	0.00	1.60	1.77
3	0.00	0.00	0.56	0.52	0.43	0.37	0.64	0.79	0.00	0.00	1.32	1.64
4	0.02	0.03	0.35	0.32	0.00	0.00	0.94	1.04	0.00	0.00	1.01	1.14
5	0.18	0.25	0.34	0.34	0.00	0.00	1.20	1.46	0.00	0.00	0.84	0.96
6	0.26	0.45	0.27	0.43	0.00	0.00	1.20	1.44	0.00	0.00	0.98	1.00
7	1.78	1.74	0.14	0.05	0.00	0.00	1.43	1.70	0.00	0.00	0.64	0.73
8	0.23	0.37	0.24	0.43	0.00	0.00	1.44	1.60	0.04	0.02	0.67	0.67
9	4.96	4.98	0.37	0.41	0.00	0.00	1.23	1.39	8.38	8.29	0.11	0.12
10	0.00	0.00	0.77	0.95	0.00	0.00	1.01	1.15	0.00	0.00	2.19	2.55
11	0.00	0.00	0.50	0.70	0.00	0.00	1.06	1.17	1.93	1.63	1.28	1.41
12	0.00	0.00	0.19	0.20	0.00	0.00	1.09	1.27	1.88	2.60	0.96	1.06
13	0.15	0.15	0.29	0.43	0.00	0.00	1.29	1.51	12.01	11.34	2.79	3.20
14	0.28	0.28	0.47	0.55	0.00	0.00	1.38	1.68	0.00	0.00	2.51	2.61
15	0.46	0.45	0.84	0.93	2.01	2.00	2.10	2.46	0.00	0.00	2.13	2.27
16	0.08	0.08	0.62	0.62	2.02	2.27	0.88	1.21	0.46	0.41	1.44	1.44
17	2.50	2.36	0.60	0.67	0.00	0.00	1.97	2.24	0.00	0.00	2.44	2.35
18	6.78	6.19	0.72	0.72	0.00	0.00	1.42	1.77	0.00	0.00	2.21	2.06
19	8.24	8.04	0.53	0.54	0.00	0.00	1.02	1.25	0.00	0.00	1.94	1.74
20	3.99	3.98	0.47	0.62	0.00	0.00	1.28	1.49	0.00	0.00	1.65	1.62
21	4.96	4.76	1.57	1.85	0.00	0.00	1.33	1.50	0.00	0.00	1.73	1.55
22	0.00	0.00	1.67	1.94	0.00	0.00	1.17	1.42	0.04	0.05	1.57	1.36
23	3.06	2.91	0.72	0.71	0.00	0.00	1.13	1.34	0.02	0.03	1.57	1.37
24	0.58	0.60	0.66	0.98	0.00	0.00	1.33	1.58	0.00	0.00	1.57	1.30
25	0.00	0.00	0.55	0.53	0.00	0.00	1.22	1.50	0.00	0.00	1.90	1.50
26	0.00	0.00	0.46	0.58	0.22	0.26	1.21	1.52	0.00	0.00	1.98	1.48
27	0.33	0.24	0.31	0.35	0.00	0.00	1.30	1.82	0.00	0.00	1.58	1.19
28	0.40	0.35	0.41	0.47	0.00	0.00	1.14	1.24	0.10	0.13	1.71	1.27
29	0.00	0.00	0.32	0.38	0.00	0.00	1.14	1.34	5.30	5.08	0.82	0.76
30					0.00	0.00	1.41	1.61	0.00	0.00	2.91	2.59
31					0.00	0.00	1.41	1.64				
TOT	39.24	38.21	16.36	18.78	5.20	5.43	37.04	43.89	30.16	29.58	47.58	46.54

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

	May 1992				June 1992				July 1992			
Day	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm
1	0.00	0.00	1.76	1.35	0.00	0.00	0.17	0.29	0.00	0.00	0.44	0.49
2	0.00	0.00	1.67	1.22	0.00	0.00	0.34	0.52	0.19	0.14	0.55	0.59
3	0.00	0.00	1.89	1.34	0.00	0.00	0.20	0.28	0.00	0.00	0.51	0.60
4	0.00	0.00	1.93	1.31	0.00	0.00	0.23	0.30	0.23	0.28	0.38	0.49
5	0.00	0.00	1.82	1.30	0.00	0.00	0.21	0.31	0.15	0.16	0.41	0.40
6	0.00	0.00	1.77	1.19	0.00	0.00	0.23	0.36	0.00	0.00	0.36	0.41
7	0.00	0.00	1.67	1.21	0.00	0.00	0.15	0.30	0.00	0.00	0.30	0.33
8	0.00	0.00	0.67	0.44	0.00	0.00	0.22	0.31	0.00	0.00	0.24	0.32
9	0.00	0.00	0.83	0.51	0.00	0.00	0.14	0.20	0.00	0.00	0.34	0.43
10	0.00	0.00	1.07	0.83	0.00	0.00	0.17	0.23	0.59	0.63	0.12	0.16
11	0.00	0.00	0.75	0.54	0.72	0.57	0.41	0.46	0.00	0.00	0.65	0.65
12	0.00	0.00	0.65	0.44	22.80	22.69	0.69	0.72	0.00	0.00	0.35	0.38
13	0.00	0.00	0.77	0.63	5.29	4.81	2.00	2.10	0.00	0.00	0.34	0.38
14	0.00	0.00	0.87	0.71	0.00	0.00	2.08	2.22	0.00	0.00	0.33	0.41
15	0.00	0.00	0.72	0.71	1.09	0.98	1.91	1.99	0.00	0.00	0.34	0.34
16	0.00	0.00	0.67	0.60	0.00	0.00	2.01	2.18	0.00	0.00	0.32	0.39
17	0.00	0.00	0.60	0.48	0.00	0.00	1.36	1.51	0.00	0.00	0.40	0.41
18	0.00	0.00	0.65	0.64	0.00	0.00	1.20	1.47	0.09	0.12	0.33	0.38
19	0.00	0.00	0.49	0.54	0.00	0.00	1.20	1.57	0.00	0.00	0.34	0.40
20	0.00	0.00	0.49	0.51	0.00	0.00	1.05	1.45	0.50	0.57	0.44	0.46
21	0.00	0.00	0.39	0.36	0.00	0.00	1.04	1.34	0.00	0.00	0.23	0.36
22	0.00	0.00	0.38	0.38	0.00	0.00	0.98	1.34	0.38	0.47	0.26	0.31
23	0.00	0.00	0.46	0.50	0.00	0.00	1.00	1.28	4.55	4.25	1.09	1.08
24	0.00	0.00	0.40	0.53	0.00	0.00	0.95	1.16	0.00	0.00	1.57	1.33
25	0.36	0.42	0.51	0.53	0.00	0.00	0.75	1.01	0.00	0.00	0.89	0.75
26	0.00	0.00	0.51	0.73	0.00	0.00	0.57	0.68	0.00	0.00	0.67	0.65
27	0.00	0.00	0.34	0.37	0.00	0.00	0.64	0.76	0.00	0.00	0.54	0.49
28	0.00	0.00	0.24	0.28	3.47	3.60	0.68	0.88	0.00	0.00	0.46	0.46*
29	0.00	0.00	0.28	0.44	0.46	0.37	2.29	2.18	0.00	0.00	0.35	0.37
30	0.00	0.00	0.33	0.41	0.00	0.00	0.89	0.91	0.00	0.00	0.37	0.33
31	0.00	0.00	0.36	0.49					0.00	0.00	0.34	0t.30
TOT	0.36	0.42	25.94	21.52	33.83	33.02	25.76	30.31	6.68	6.62	14.26	14.88

Table 2.--*Daily and monthly precipitation and evapotranspiration for grass and sage lysimeter sites, May 1, 1990, to September 30, 1992--Continued*

Day	August 1992				September 1992			
	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)	PRG (mm)	PRS (mm)	ETG (mm)	ETS (mm)
1	0.00	0.00	0.31	0.24	0.00	0.00	0.45	0.32
2	0.00	0.00	0.30	0.39	0.00	0.00	0.40	0.29
3	0.00	0.00	0.23	0.20	0.00	0.00	0.44	0.24
4	0.00	0.00	0.20	0.09	0.00	0.00	0.26	0.17
5	0.00	0.00	0.14	0.25	0.00	0.00	0.31	0.16
6	0.00	0.00	0.01	0.22	0.00	0.00	0.28	0.13
7	0.00	0.00	0.18	0.10	0.00	0.00	0.41	0.07
8	0.00	0.00	0.20	0.21	0.00	0.00	0.16	0.15
9	0.00	0.00	0.18	0.14	0.00	0.00	0.31	0.15
10	0.00	0.00	0.21	0.20	0.00	0.00	0.23	0.09
11	0.00	0.00	0.24	0.14	0.00	0.00	0.13	0.15
12	0.00	0.00	0.10	0.16	0.00	0.00	0.27	0.08
13	0.00	0.00	0.27	0.28	0.00	0.00	0.22	0.03
14	0.00	0.00	0.26	0.28	0.53	0.41	0.19	0.00
15	0.00	0.00	0.19	0.19	3.92	3.83	0.50	0.48
16	0.00	0.00	0.22	0.19	0.04	0.17	1.12	1.04
17	0.00	0.00	0.17	0.17	0.00	0.00	0.91	0.88
18	0.00	0.00	0.22	0.17	0.00	0.00	0.62	0.43
19	0.00	0.00	0.16	0.12	0.77	0.69	1.00	0.98
20	0.00	0.00	0.15	0.12	0.00	0.00	0.31	0.23
21	4.29	3.78	0.11	0.13	0.00	0.00	0.26	0.33
22	16.68	10.98	2.35	2.07	0.00	0.00	0.31	0.30*
23	0.00	0.00	2.66	1.96	2.76	2.51	0.66	0.52
24	0.07	0.18	1.63	1.26	0.53	0.47	1.13	1.07
25	0.00	0.00	1.25	0.91	0.00	0.00	0.62	0.48
26	0.00	0.00	0.90	0.73	0.00	0.00	0.27	0.23
27	0.00	0.00	0.80	0.65	0.00	0.00	0.38	0.21
28	0.00	0.00	0.66	0.56	0.00	0.00	0.26	0.14
29	0.00	0.00	0.64	0.44	0.00	0.00	0.17	0.17
30	0.00	0.00	0.53	0.33	0.00	0.00	0.24	0.19
31	0.00	0.00	0.44	0.36				
TOT	21.04	14.94	15.91	13.26	8.55	8.08	12.82	9.71

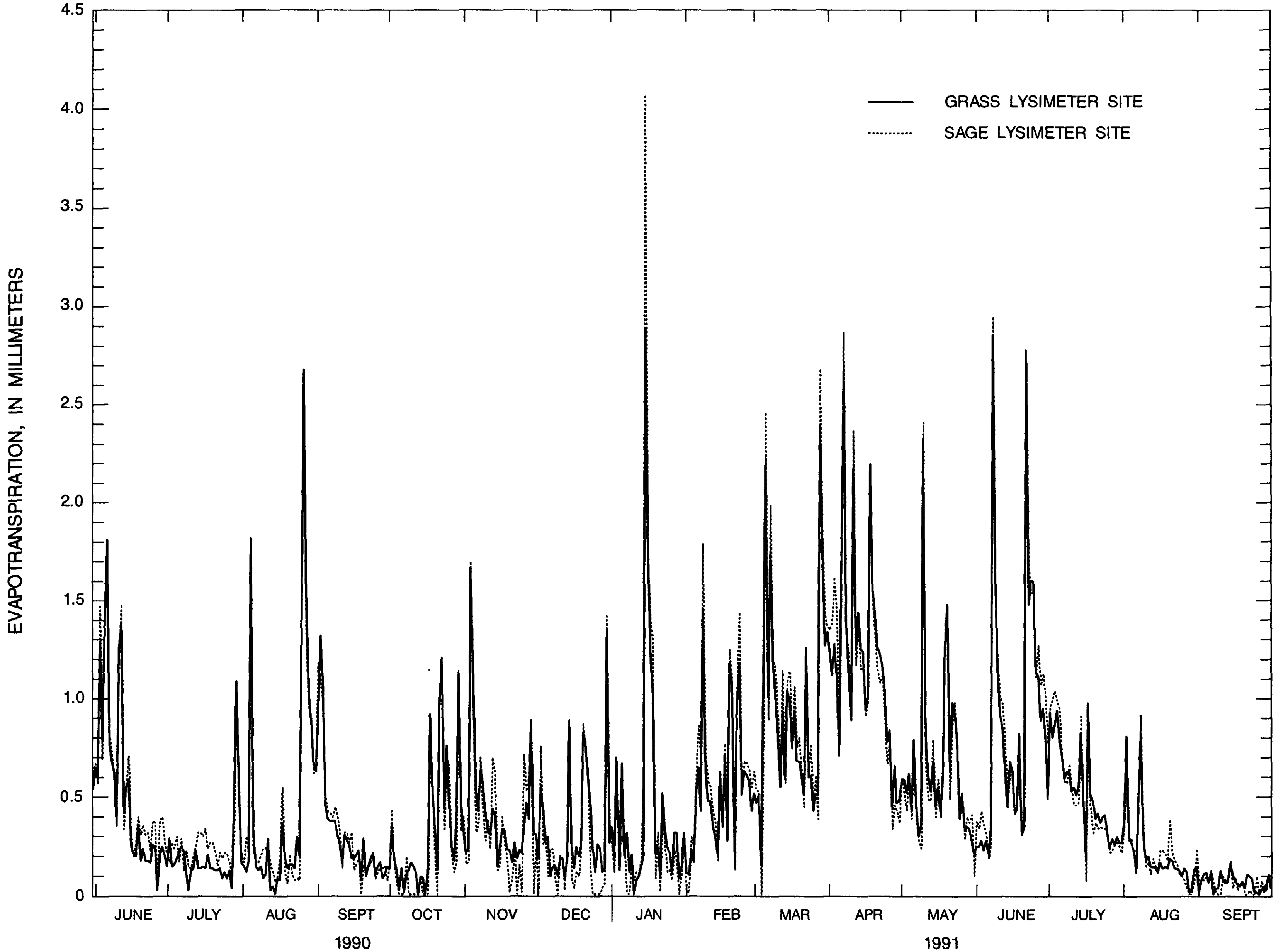

Figure 13.--Daily evapotranspiration from weighing lysimeters at the grass and sage lysimeter sites, May 30, 1990 to September 30, 1991. Evapotranspiration estimates are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

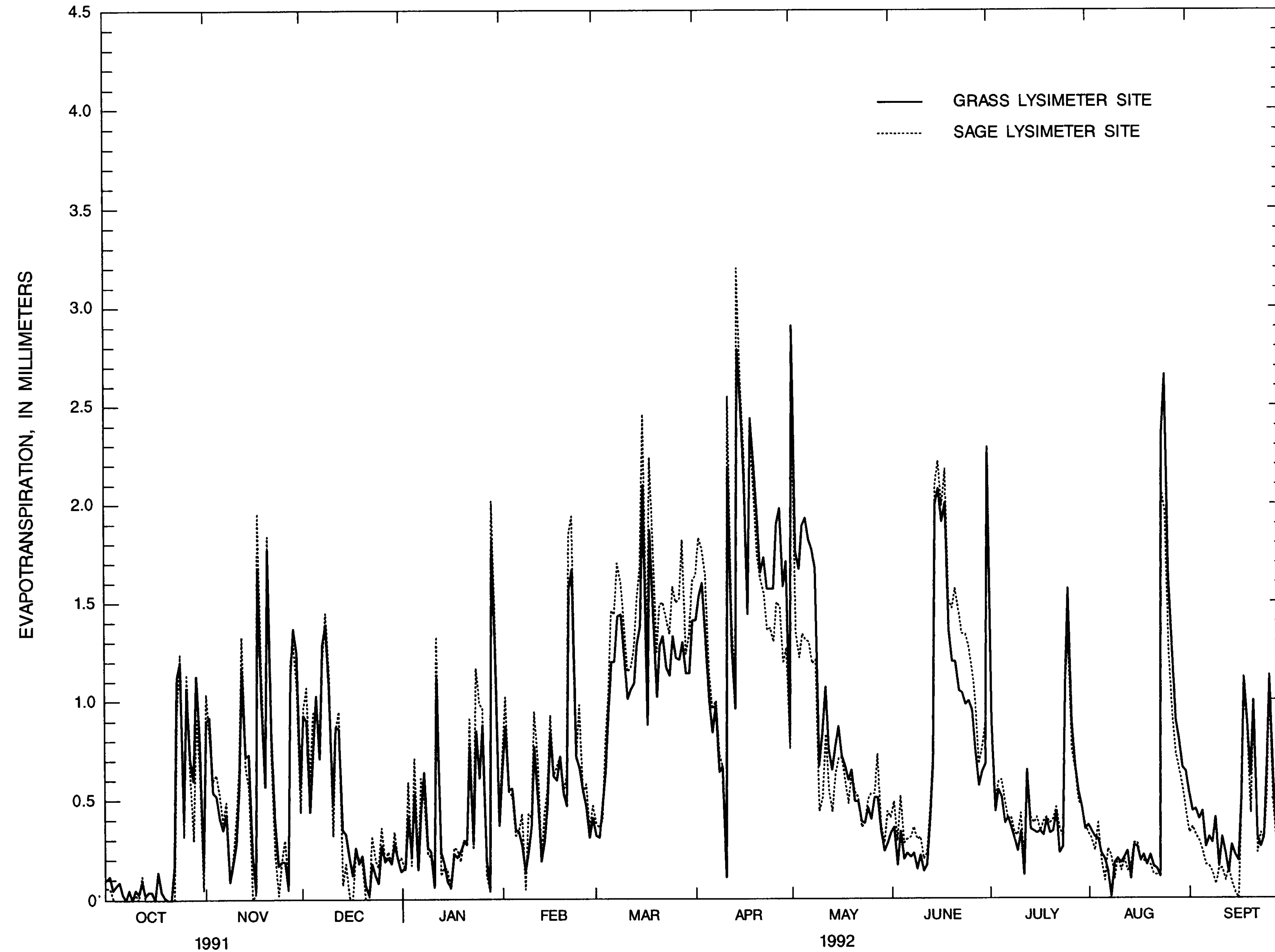

Figure 14.--Daily evapotranspiration from weighing lysimeters at the grass and sage lysimeter sites, October 1, 1991 to September 30, 1992. Evapotranspiration estimates are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

Table 3.--*Daily and monthly precipitation and evapotranspiration at the grass lysimeter site, April 2 to May 13, 1991, and at the sage lysimeter site, July 23-30, 1992*

[Evapotranspiration and precipitation estimates for the weighing lysimeters are based on data collected and provided by Battelle, Pacific Northwest Laboratories; mm, millimeters; PRC, precipitation measured by tipping-bucket rain gage; PRW, average precipitation measured by two weighing lysimeters; WL, average evapotranspiration measured by two weighing lysimeters; BR, evapotranspiration calculated with the Bowen-ratio method; TOT, total; *, partially estimated; --, no measurement]

	Grass lysimeter site								Sage lysimeter site		
	April 1991				May 1991				July 1992		
Day	PRC (mm)	PRW (mm)	WL (mm)	BR (mm)	PRC (mm)	PRW (mm)	WL (mm)	BR (mm)	PRW (mm)	WL (mm)	BR (mm)
1	--	--	--	--	0.00	0.16	0.51	0.30	--	--	--
2	0.25	0.22	1.10	0.68	0.00	0.00	0.61	0.22	--	--	--
3	0.25	0.60	0.70	0.31	0.00	0.35	0.43	0.13	--	--	--
4	6.10	6.13	1.69	1.32	0.00	0.03	0.78	0.30	--	--	--
5	0.00	0.00	2.66	1.15	0.00	0.00	0.45	0.31	--	--	--
6	0.00	0.00	1.37	0.41	0.00	0.00	0.29	0.24	--	--	--
7	0.00	0.00	1.13	0.55	1.78	1.80	0.35	0.31	--	--	--
8	2.03	2.41	0.88	0.20	2.54	3.14	2.32	1.11	--	--	--
9	0.25	0.36	2.17	1.41	0.00	0.00	0.81	0.32	--	--	--
10	0.00	0.00	1.25	0.42	0.00	0.00	0.60	0.16	--	--	--
11	0.00	0.00	1.43	0.24	0.00	0.14	0.52	0.36	--	--	--
12	0.00	0.00	1.24	0.23	0.25	0.36	0.67	0.44	--	--	-
13	0.00	0.00	1.23	0.33	0.00	0.00	0.44	0.17	--	--	--
14	0.25	0.53	0.93	0.32	--	--	--	--	--	--	--
15	5.33	5.20	1.00	0.45	--	--	--	--	--	--	--
16	0.00	0.09	2.19	0.54	--	--	--	--	--	--	--
17	0.00	0.00	1.54	0.30	--	--	--	--	--	--	--
18	0.00	0.00	1.42	0.30	--	--	--	--	--	--	--
19	0.00	0.00	1.25	0.54	--	--	--	--	--	--	--
20	0.00	0.00	1.22	0.33	--	--	--	--	--	--	--
21	0.00	0.00	1.16	0.44	--	--	--	--	--	--	--
22	0.00	0.00	1.04	0.21	--	--	--	--	--	--	--
23	0.00	0.22	0.77	0.29	--	--	--	--	4.25	1.08	1.46
24	0.00	0.11	0.83	0.48	--	--	--	--	0.00	1.33	0.56
25	0.00	0.00	0.43	0.28	--	--	--	--	0.00	0.75	0.54
26	0.00	0.00	0.65	0.27	--	--	--	--	0.00	0.65	0.56
27	0.00	0.00	0.46	0.39	--	--	--	--	0.00	0.49	0.72
28	0.00	0.00	0.47	0.12	--	--	--	--	0.00	0.46*	0.56*
29	0.00	0.00	0.58	0.26	--	--	--	--	0.00	0.37	0.36
30	0.00	0.00	0.58	0.22	--	--	--	--	0.00	0.33	0.48
31					--	--	--	--	--	--	--
TOT	14.46	15.87	33.37	12.93	4.57	6.16	8.78	4.37	4.25	5.46	5.24

Unfortunately, DEW-10 problems were also partly responsible for much erroneous and unreasonable data at the sage lysimeter site in 1992. The inexplicable loss of calibration on the DEW-10 and consistent icing of its mirror, coupled with data logger problems and animal damage to other parts of the Bowen-ratio instruments from May to September 1992, allowed only one week of apparently accurate data in late July. Although the Bowen-ratio ET was 96 percent of lysimeter ET for July 23-30, 1992 (table 3), the r^2 for the daily ET estimates was 0.22, indicating very large variability between the two methods on a daily basis. DEW-10 problems may have contributed to the poor daily correlation between sage site Bowen-ratio ET and lysimeter ET during this period. There is no way to be certain, however, because the data appeared reasonable. As at the grass lysimeter site, subsequent investigations comparing Bowen-ratio ET and lysimeter ET at the sage lysimeter site in 1993 and 1994 did not show large differences between the two methods except in the fall, when Bowen-ratio ET averaged six times lysimeter ET when sage plants were in bloom (S. Tomlinson, U.S. Geological Survey, written commun., 1994).

Snively Basin Site

Seasonal patterns of lysimeter ET at the grass lysimeter site were similar to those of Penman-Monteith ET for the Snively Basin site except for late spring (table 4, figs. 15-16). During late spring, ET at the Snively Basin site was often 2 to 5 times higher than ET at the grass lysimeter site. While grasses senesced (grew old) at the grass lysimeter site in April or May, they did not senesce at the Snively Basin site until June or July. The denser cover of grasses at the Snively Basin site, compared with the cover at the lysimeter site, reflected a more favorable long-term growth environment in Snively Basin. Conditions at the Snively Basin site are wetter and cooler than conditions at the grass lysimeter site. Although the Snively Basin site is only 5 km from the grass lysimeter site, it is 200 m higher in altitude and, during the study period (May 30, 1990 to September 30, 1992), received 13 percent more precipitation than the grass lysimeter site. Data collected by Stone and others (1983) showed about 17 percent more precipitation at Snively Basin than in the area around the lysimeters. Coupled with a slightly cooler environment, this extra water allowed the grasses at Snively Basin a longer growing season than at the grass lysimeter site.

During the study period at the Snively Basin site (May 1990 to September 1992), latent-heat fluxes and ET estimated with the Bowen-ratio method agreed well with latent-heat fluxes and ET estimated with the Penman-Monteith method (table 4, fig. 10). The r^2 for the Bowen-ratio and Penman-Monteith ET estimates was 0.95 (Tomlinson, 1995). The close correlation between the two methods was due primarily to using the Bowen-ratio latent-heat fluxes to calibrate the Penman-Monteith method for the canopy resistance. The results of the methods are not independent.

For the period August 20, 1990 to September 30, 1992 at the Snively Basin site, totals of model ET agreed closely with totals of Penman-Monteith ET. The model yielded 512 mm of ET while the Penman-Monteith estimates totalled 510 mm. However, on a daily, monthly, and seasonal basis, there was much more difference (figs. 17-18, table 4). The r^2 for the daily values of Penman-Monteith ET and model ET was 0.57. Daily estimates of Penman-Monteith ET differed from daily model ET by an average of 25.2 percent, with a range of -100 to 2,400 percent difference. The average of the monthly differences between model ET and Penman-Monteith ET was 4.0 percent, but with a wide range of differences:

	1990	1991	1992
January	--	19.1	-35.4
February	--	-14.8	-43.1
March	--	-36.2	9.4
April	--	-39.2	28.8
May	--	34.4	36.6
June	--	35.0	34.9
July	--	-4.7	-19.7
August	60.9 (August 20-31)	-64.0	-39.5
September	145	-100	-26.9
October	-19.3	-55.0	--
November	-11.0	-37.8	--
December	83.8	-46.3	--

(Text continued on p. 60.)

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992*

[mm, millimeters; PRC, precipitation measured by tipping-bucket rain gage; DPM, evapotranspiration, deep-percolation model; BR, evapotranspiration, Bowen-ratio method; PM, evapotranspiration, Penman-Monteith method; RC, canopy resistance; TOT, monthly totals of daily precipitation and evapotranspiration; TR, data suggests trace of precipitation; *, partly estimated; #, totals for June; --, no measurement]

	May-June 1990				July 1990				August 1990			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
May												
31	0.51	0.97	0.98	--								
June												
1	0.00	1.38	1.36	--	0.00	0.32*	0.32	--	0.00	0.36	0.33	--
2	0.00	0.76	0.80	--	1.52	0.36*	0.54	--	0.00	--	0.30	--
3	0.00	1.99	1.85	--	0.00	0.30*	0.36	--	0.00	--	0.34	--
4	0.00	1.35	1.54	--	0.00	0.30*	0.44	--	0.00	--	0.35	--
5	0.00	0.98	0.84	--	0.00	0.24*	0.40	--	0.00	--	0.36	--
6	6.60	2.06	1.64	--	0.00	0.24*	0.27	--	0.00	--	0.43	--
7	0.00	1.55	1.39	--	0.00	0.22*	0.27	--	0.00	--	0.34	--
8	0.00	0.73	0.94	--	0.00	0.32*	0.38	--	0.00	--	0.21	--
9	0.00	0.62	0.61	--	0.00	0.29*	0.38	--	0.00	--	0.13	--
10	1.27	1.69	1.97	--	0.00	0.65*	0.45	--	0.00	--	0.20	--
11	0.00	1.15	1.27	--	0.00	0.37	0.41	--	0.00	--	0.18	--
12	0.00	0.75	0.86	--	0.00	0.33	0.38	--	0.00	--	0.22	--
13	0.00	0.92	0.87	--	0.00	0.32	0.35	--	0.00	--	0.21	--
14	0.00	1.22	1.25	--	0.00	0.44	0.47	--	0.00	--	0.21	--
15	0.00	0.93	0.99	--	0.00	0.37	0.39	--	0.00	--	0.13	--
16	0.00	0.95	1.07	--	0.00	0.37	0.33	--	0.00	--	0.10	--
17	0.00	0.93	0.99	--	0.00	0.28	0.29	--	TR	--	0.26	--
18	0.00	1.01	1.06	--	0.00	0.26	0.29	--	0.00	--	0.17	--
19	0.51	1.51	1.46	--	0.00	0.40	0.43	--	TR	--	0.46	--
20	0.00	0.80	0.62	--	0.00	0.29	0.32	--	0.00	--	0.16	0.00
21	0.00	1.13	1.08	--	0.00	0.38	0.36	--	28.19	1.56*	1.49*	1.52
22	0.00	0.43	0.45	--	0.00	0.38	0.36	--	0.00	--	2.30*	2.08
23	0.00	0.96	0.86	--	0.00	0.40	0.38	--	0.00	--	1.17*	1.98
24	0.00	0.87	0.88	--	TR	0.55	0.61	--	0.00	--	1.04*	1.68
25	0.00	0.37*	0.42	--	1.27	0.98	1.01	--	0.00	--	0.74*	1.32
26	0.00	0.27*	0.32	--	0.00	0.23	0.24	--	0.00	--	0.66*	1.45
27	0.00	0.23*	0.30	--	0.00	0.19	0.21	--	0.00	--	0.56*	1.55
28	0.00	0.22*	0.31	--	0.00	0.27	0.21	--	0.00	--	0.53*	1.55
29	0.00	0.29*	0.39	--	0.00	0.29	0.26	--	0.00	--	0.72*	2.26
30	0.00	0.24*	0.35	--	0.00	0.27	0.29	--	3.56	--	1.18*	1.07
31					0.00	0.26	0.27	--	0.00	--	0.54*	1.27
TOT	8.38#	28.29#	28.74#	--	2.79	10.87	11.67	--	31.75	--	16.02	--

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	September 1990				October 1990				November 1990			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.00	--	0.37*	1.30	0.00	--	0.04	0.08	0.00	--	0.94	0.48
2	0.00	--	0.35*	1.07	0.00	--	0.03	0.05	0.00	--	0.40	0.25
3	0.00	--	0.21*	1.02	0.00	--	0.03	0.08	0.00	--	0.20	0.15
4	0.00	--	0.24*	1.07	0.00	--	0.02	0.08	0.00	--	0.30	0.43
5	0.00	--	0.28*	1.09	0.00	--	0.02	0.05	0.00	--	0.29	0.26
6	0.00	--	0.28*	0.89	0.00	--	0.02	0.05	0.00	--	0.19	0.25
7	0.00	--	0.15	0.51	0.00	--	0.02	0.05	0.00	--	0.14	0.28
8	0.00	--	0.23	0.58	0.00	--	0.02	0.05	0.00	--	0.10	0.20
9	0.00	--	0.22	0.58	0.00	--	0.02	0.05	0.00	--	0.12	0.20
10	0.00	--	0.20	0.51	0.00	--	0.02	0.03	0.00	--	0.14	0.33
11	0.00	--	0.24	0.48	0.00	--	0.02	0.03	0.00	--	0.22	0.38
12	0.00	--	0.16	0.36	0.00	--	0.02	0.03	0.00	--	0.19	0.33
13	0.00	--	0.14	0.30	0.00	--	0.01	0.03	0.00	--	0.19	0.28
14	0.00	--	0.18	0.33	2.29	1.18	0.89	0.46	0.00	--	0.16	0.18
15	0.00	--	0.10	0.23	0.00	--	0.65	0.89	0.00	--	0.15	0.23
16	0.00	--	0.11	0.20	0.00	--	0.35	0.05	0.00	--	0.15	0.18
17	0.00	--	0.14	0.23	0.00	--	0.15	0.03	0.00	--	0.07	0.13
18	0.00	--	0.14	0.23	6.35	--	0.64	0.56	0.00	--	0.13	0.15
19	0.00	--	0.15	0.20	0.00	--	1.24	0.71	0.00	--	0.09	0.13
20	0.00	--	0.13	0.20	0.00	--	0.41	0.10	0.00	--	0.08	0.13
21	0.00	--	0.17	0.20	1.02	--	0.70	0.69	0.00	--	0.04	0.13
22	0.00	--	0.17	0.20	0.00	--	0.42	0.43	0.00	--	0.08	0.15
23	0.00	--	0.14	0.20	0.00	--	0.22	0.08	0.00	--	0.06	0.13
24	0.00	--	0.14	0.18	0.00	--	0.19	0.10	0.25	--	0.17	0.33
25	0.00	--	0.10	0.18	3.05	--	0.27	1.09	2.03	--	1.04	0.36
26	0.00	--	0.14	0.15	0.00	--	0.92	0.25	0.00	--	0.68	0.26
27	0.00	--	0.10	0.13	0.00	--	0.45	0.15	0.00	--	0.35	0.25
28	0.00	--	0.13	0.13	0.00	--	0.24	0.12	0.00	--	0.16	0.20
29	0.00	--	0.12	0.13	2.03	--	0.20	0.71	1.52	--	0.71	0.30
30	0.00	--	0.07	0.10	14.22	--	0.55	0.38	0.00	--	0.68	0.26
31					0.51	--	1.07	0.48				
TOT	0.00	--	5.30	12.98	29.47	--	9.85	7.95	3.80	--	8.22	7.32

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	December 1990				January 1991				February 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.25	--	0.58	0.25	0.00	--	0.12	0.25	0.00	--	0.12	0.18
2	0.00	--	0.23	0.25	0.00	--	0.36	0.18	2.03	--	0.94	0.51
3	0.00	--	0.25	0.23	0.00	--	0.10	0.18	0.76	--	0.58	0.36
4	0.00	--	0.14	0.15	0.00	--	0.17	0.23	2.03	--	0.46	0.33
5	0.00	--	0.08	0.15	0.00	--	0.10	0.18	2.79	--	0.99	0.56
6	0.00	--	0.09	0.15	0.76	--	0.07	0.25	0.00	--	0.66	0.36
7	0.00	--	0.13	0.15	1.78	--	0.11	0.25	0.00	--	0.43	0.25
8	0.00	--	0.07	0.15	0.00	--	0.12	0.30	0.00	--	0.25	0.30
9	5.59	--	0.09	0.26	2.29	--	0.16	0.28	0.00	--	0.21	0.30
10	8.64	--	0.16	0.26	1.52	--	0.08	0.26	0.00	--	0.12	0.18
11	0.00	--	0.40	0.25	7.88	--	0.01	0.25	0.00	--	0.05	0.18
12	0.00	--	0.23	0.25	0.25	--	0.58	0.36	1.27	--	0.10	0.33
13	0.00	--	0.20	0.23	0.25	--	0.49	0.36	2.79	--	0.22	0.25
14	0.00	--	0.06	0.18	0.51	--	0.27	0.26	0.00	--	0.19	0.28
15	0.00	--	0.24	0.18	0.25	--	0.41	0.33	0.25	--	0.36	0.38
16	0.00	--	0.06	0.18	0.25	--	0.22	0.26	0.00	--	1.01	0.46
17	0.00	--	0.09	0.18	0.00	--	0.38	0.25	0.00	--	0.66	0.38
18	1.27	--	0.09	0.25	0.25	--	0.23	0.25	0.00	--	0.16	0.28
19	2.79	--	0.13	0.41	0.00	--	0.38	0.23	0.00	--	0.12	0.53
20	0.00	--	0.05	0.41	0.00	--	0.33	0.18	0.76	--	1.62	0.71
21	1.78	--	0.06	0.66	0.00	--	0.21	0.18	0.00	--	0.94	0.41
22	0.00	--	0.07	0.41	0.00	--	0.22	0.18	0.00	--	0.76	0.46
23	0.00	--	0.08	0.38	0.00	--	0.21	0.15	0.00	--	0.52	0.51
24	0.00	--	0.07	0.28	0.00	--	0.09	0.18	0.00	--	0.34	0.51
25	0.00	--	0.09	0.20	0.00	--	0.03	0.18	0.00	--	0.28	0.48
26	0.25	--	0.12	0.36	0.00	--	0.08	0.20	0.00	--	0.34	0.56
27	0.00	--	0.41	0.18	0.00	--	0.10	0.20	0.00	--	0.35	0.56
28	3.56	--	0.07	0.66	0.00	--	0.08	0.20	0.00	--	0.32	0.56
29	0.25	--	0.09	0.51	0.00	--	0.10	0.18				
30	1.78	--	0.07	0.33	0.00	--	0.05	0.18				
31	1.78	--	0.45	0.61	0.00	--	0.10	0.18				
TOT	27.94	--	4.95	9.10	15.99	--	5.96	7.10	12.68	--	13.10	11.16

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	March 1991				April 1991				May 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.51	--	0.16	0.18	0.00	1.84	1.85	1.37	0.00	1.93	2.05	1.91
2	9.91	--	0.58	0.48	0.51	2.51	2.54	0.99	TR	3.03	3.18	1.70
3	7.11	--	0.75	0.71	0.00	1.25	1.11	0.81	0.00	2.44	2.58	1.90
4	5.08	--	0.59	0.41	4.32	1.77	1.78	1.02	0.00	1.53	1.50	2.16
5	0.00	--	1.28	0.43	0.00	2.14	2.42	1.12	0.00	0.79	0.85	1.50
6	0.00	--	0.79	0.46	0.00	1.64	1.76	0.81	TR	1.07	1.00	1.67
7	0.00	--	0.63	0.56	0.00	1.73	1.76	0.84	2.54	0.73	0.91	1.63
8	0.00	--	0.48	0.53	5.84	1.44	1.58	1.04	2.54	2.24	2.28	1.63
9	0.00	--	0.31	0.51	0.51	2.49	2.50	0.94	0.00	0.98	0.99	1.30
10	0.00	--	0.40	0.46	0.00	1.72	1.92	0.76	0.00	1.11	1.15	1.68
11	1.27	--	0.27	0.36	0.00	2.10	2.20	1.32	0.00	1.04	1.17	1.60
12	2.54	--	1.10	0.64	0.00	2.01	2.09	1.50	0.25	0.82	0.96	1.75
13	0.00	--	1.30	0.58	0.00	2.15	2.38	1.60	0.00	1.42	1.58	1.52
14	0.00	--	0.98	0.43	TR	2.68	2.31	1.12	0.00	1.82	2.09	2.03
15	0.00	--	0.97	0.51	6.10	1.71	1.33	1.17	0.00	1.17	1.26	2.08
16	0.00	--	1.01	0.61	0.00	2.44	2.41	1.32	4.06	0.64	0.65	1.35
17	0.00	--	1.03	0.64	0.00	2.70	2.69	1.35	3.81	1.02	1.16	1.40
18	0.51	--	0.47	0.63	0.00	2.04	2.02	1.57	0.76	2.39	1.83	1.65
19	0.51	1.11	0.73	0.53	0.00	3.47	3.34	1.73	0.00	0.22	0.20	1.14
20	0.00	1.55	1.36	0.74	0.00	3.42	3.58	2.01	0.00	2.21	2.17	2.21
21	0.00	1.23	1.34	0.81	0.00	3.83	3.80	2.26	0.00	1.79	1.78	2.59
22	0.00	1.23	1.12	0.56	0.00	3.10	3.09	2.16	0.00	0.91	0.99	2.54
23	0.00	0.99	1.02	0.58	0.00	2.53	2.55	1.90	0.00	1.01	1.20	2.11
24	10.92	1.00	0.65	0.58	0.25	2.18	2.20	1.14	0.00	0.54	0.72	1.65
25	4.06	.76	0.64	0.28	0.00	1.70	1.63	1.12	0.00	0.56	0.57	1.50
26	4.57	2.43	2.27	0.61	0.00	2.05	2.05	1.22	0.00	0.61	0.61	1.65
27	0.00	1.56	1.55	0.97	0.00	1.88	1.92	1.30	0.00	0.88	0.80	1.80
28	0.00	1.45	1.16	0.74	0.00	1.88	1.73	1.30	0.00	1.07	0.98	1.98
29	0.00	1.43	1.49	0.86	0.00	1.84	1.85	1.65	0.00	0.74	0.81	1.17
30	0.00	1.74	1.41	1.19	0.00	2.57	2.16	2.01	0.00	0.78	0.83	1.32
31	0.00	1.60	1.53	1.17	0.00	1.33	1.30	1.85				
TOT	46.99	--	29.37	18.75	17.53	66.81	66.55	40.45	13.96	38.82	40.15	53.97

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	June 1991				July 1991				August 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.00	1.39	1.40	2.03	0.00	1.38	1.25	2.06	0.00	--	0.25	0.10
2	0.00	1.06	1.05	1.85	0.00	1.92	1.85	2.24	0.00	--	0.36	0.10
3	0.00	0.61	0.64	1.09	0.00	1.64	1.70	1.96	0.00	--	0.32	0.10
4	0.00	0.54	0.49	1.14	0.00	2.21	2.17	1.55	0.00	--	0.35	0.08
5	7.37	1.21	1.30	1.40	0.00	1.61	1.57	1.24	0.00	--	0.23	0.05
6	6.10	3.78	3.57	2.16	0.00	1.95	1.92	0.99	0.76	--	0.60	0.86
7	0.00	1.49	1.48	1.57	0.00	--	1.58	0.97	0.25	--	0.70	0.33
8	0.00	2.15	1.87	1.80	0.00	--	0.94	0.99	0.00	--	0.34	0.05
9	0.00	0.96	1.05	1.90	0.00	--	0.85	0.84	0.00	--	0.26	0.05
10	0.00	1.39	1.21	2.16	0.00	--	0.46	0.81	0.00	--	0.14	0.03
11	0.00	1.36	1.26	0.97	0.00	--	0.69	0.79	0.00	--	0.23	0.03
12	0.00	0.70	0.73	0.94	0.00	--	0.64	0.74	0.00	--	0.15	0.03
13	1.02	1.02	0.88	1.50	0.51	0.68	0.68	1.07	0.00	--	0.14	0.03
14	0.00	0.89	0.87	0.97	0.00	0.62	0.51	0.51	0.00	--	0.10	0.03
15	0.00	0.83	0.82	0.99	0.00	0.24	0.25	0.36	0.00	--	0.10	0.03
16	0.00	0.83	0.83	0.71	1.27	0.77	0.73	1.45	0.00	--	0.16	0.03
17	0.00	1.13	1.12	0.97	TR	0.74	0.77	0.33	0.00	--	0.13	0.03
18	0.00	0.59	0.55	1.04	0.00	0.55	0.47	0.38	0.00	--	0.15	0.03
19	7.11	0.81	0.94	1.90	0.00	0.57	0.49	0.36	0.00	--	0.14	0.03
20	21.08	1.27	1.50	1.22	0.00	0.65	0.50	0.38	0.00	--	0.13	0.03
21	1.52	1.38	1.35	1.85	0.00	0.67	0.58	0.30	0.00	--	0.13	0.03
22	TR	0.79	0.73	1.93	0.00	--	0.44	0.30	0.00	--	0.15	0.03
23	0.00	0.97	0.97	2.51	0.00	--	0.40	0.28	0.00	--	0.08	0.00
24	0.00	0.70	0.69	2.44	0.00	--	0.42	0.25	0.00	--	0.06	0.00
25	0.00	0.95	0.86	2.39	0.00	--	0.34	0.18	0.00	--	0.08	0.00
26	0.00	1.58	1.53	2.11	0.00	--	0.40	0.18	0.00	--	0.06	0.00
27	0.00	1.73	1.72	2.31	0.00	--	0.24	0.18	0.00	--	0.08	0.00
28	0.00	1.56	1.41	2.11	0.00	--	0.24	0.18	0.00	--	0.03	0.00
29	0.25	1.11	1.20	1.32	0.00	--	0.25	0.13	0.00	--	0.06	0.00
30	TR	2.33	2.42	1.91	0.00	--	0.22	0.13	0.00	--	0.08	0.00
				0.31	0.51	--	0.41	0.64	0.00	--	0.08	0.00
TOT	44.45	37.11	36.44	49.19	2.29	--	23.91	22.78	1.01	--	5.87	2.11

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	September 1991				October 1991				November 1991			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.00	--	0.04	0.00	TR	--	0.09	0.00	0.00	--	0.18	0.25
2	0.00	--	0.06	0.00	0.00	--	0.15	0.00	0.00	--	0.26	0.33
3	0.00	--	0.06	0.00	0.00	--	0.19	0.00	3.05	--	0.71	0.25
4	0.00	--	0.09	0.00	0.00	0.16*	0.18	0.00	3.30	--	0.43	0.30
5	0.00	--	0.08	0.00	0.00	0.20*	0.23	0.00	6.86	--	0.28	0.36
6	0.00	--	0.08	0.00	0.00	0.13*	0.15	0.00	0.00	--	0.21	0.31
7	0.00	--	0.05	0.00	0.00	0.18*	0.21	0.00	0.25	--	0.23	0.26
8	0.00	--	0.03	0.00	0.00	0.12*	0.11	0.00	0.51	--	0.18	0.26
9	0.00	--	0.03	0.00	0.00	0.16*	0.17	0.00	1.02	--	0.24	0.25
10	0.00	--	0.05	0.00	0.00	0.15*	0.16	0.00	0.00	--	0.29	0.25
11	0.00	--	0.06	0.00	0.00	0.15*	0.18	0.00	0.00	--	0.42	0.53
12	0.00	--	0.06	0.00	0.00	0.18*	0.17	0.00	0.00	--	0.87	0.38
13	0.00	--	0.04	0.00	0.00	0.12*	0.14	0.00	0.00	--	0.81	0.25
14	0.00	--	0.05	0.00	0.00	0.12*	0.15	0.00	0.00	--	0.55	0.25
15	0.00	--	0.04	0.00	0.00	0.16*	0.19	0.00	0.00	--	0.19	0.18
16	0.00	--	0.06	0.00	0.00	--	0.26	0.00	8.38	--	0.32	0.30
17	0.00	--	0.04	0.00	0.00	0.12*	0.12	0.00	0.25	--	1.46	0.25
18	0.00	--	0.05	0.00	0.00	0.21*	0.28	0.00	0.00	--	0.80	0.33
19	0.00	--	0.06	0.00	0.00	0.11*	0.13	0.00	6.86	--	1.21	0.25
20	0.00	--	0.05	0.00	0.00	0.15*	0.16	0.00	0.25	--	0.68	0.28
21	0.00	--	0.04	0.00	TR	--	0.27	0.00	0.00	--	0.52	0.28
22	0.00	--	0.03	0.00	4.57	0.15*	0.14	0.61	0.00	--	0.33	0.26
23	0.00	--	0.04	0.00	2.29	0.47	0.67	0.53	0.76	--	0.20	0.25
24	0.00	--	0.05	0.00	8.38	0.26	0.55	0.48	5.33	--	0.19	0.25
25	0.00	--	0.06	0.00	6.60	0.11	0.25	0.38	1.52	--	0.20	0.31
26	0.00	--	0.06	0.00	4.06	--	0.30	0.30	5.59	--	0.17	0.26
27	0.00	--	0.06	0.00	0.25	--	0.26	0.33	5.33	--	0.55	0.26
28	0.00	--	0.05	0.00	0.00	--	0.36	0.26	0.00	--	0.52	0.26
29	0.00	--	0.06	0.00	4.83	--	0.60	0.26	5.08	--	0.25	0.25
30	0.00	--	0.06	0.00	0.00	--	0.67	0.25	0.00	--	0.34	0.25
31	0.00	--	0.63	0.00								
TOT	0.00	--	1.59	0.00	31.23	--	8.12	3.65	54.34	--	13.59	8.45

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	December 1991				January 1992				February 1992			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.00	--	0.58	0.28	0.00	--	0.12	0.18	0.00	--	0.65	0.26
2	0.00	--	0.81	0.25	1.27	--	0.37	0.28	0.00	--	0.57	0.26
3	0.00	--	0.64	0.20	0.00	--	0.19	0.26	0.00	--	0.45	0.25
4	0.00	--	0.80	0.18	3.05	--	0.60	0.26	0.00	--	0.48	0.23
5	5.08	--	1.59	0.26	0.00	--	0.11	0.25	0.00	--	0.26	0.20
6	4.32	--	0.39	0.26	6.10	--	0.10	0.25	0.00	--	0.37	0.18
7	0.00	--	0.63	0.25	0.00	--	0.09	0.25	1.54	--	0.23	0.26
8	0.00	--	0.70	0.25	0.00	--	0.03	0.25	0.00	--	0.30	0.25
9	0.00	--	0.73	0.31	0.00	--	0.11	0.18	5.08	--	0.20	0.25
10	0.00	--	0.59	0.18	1.27	--	0.02	0.26	0.00	--	0.52	0.30
11	0.00	--	0.99	0.23	0.00	--	0.99	0.25	0.00	--	0.49	0.41
12	0.00	--	0.74	0.18	0.00	--	0.18	0.25	0.00	--	0.23	0.23
13	0.00	--	0.26	0.18	0.00	--	0.30	0.18	0.00	--	0.46	0.33
14	0.00	--	0.07	0.18	0.00	--	0.25	0.18	0.00	--	0.21	0.23
15	0.00	--	0.12	0.18	0.25	--	0.27	0.25	0.51	--	0.43	0.38
16	0.00	--	0.12	0.18	4.06	--	0.28	0.28	0.00	--	0.67	0.31
17	0.00	--	0.17	0.18	0.00	--	0.44	0.26	2.03	--	0.68	0.46
18	2.03	--	0.21	0.26	0.00	--	0.14	0.25	7.11	--	1.06	0.33
19	0.00	--	0.16	0.26	0.00	--	0.16	0.18	5.84	--	0.42	0.41
20	0.00	--	0.13	0.25	0.00	--	0.19	0.18	4.57	--	0.43	0.38
21	0.00	--	0.24	0.20	0.00	--	0.47	0.18	5.59	--	2.52	0.74
22	3.30	--	0.06	0.26	0.25	--	0.70	0.25	0.00	--	1.63	0.51
23	3.81	--	0.26	0.26	0.76	--	1.00	0.36	2.29	--	0.90	0.43
24	1.02	--	0.28	0.25	0.25	--	0.71	0.38	0.51	--	0.65	0.41
25	0.00	--	0.27	0.25	0.00	--	0.75	0.38	0.00	--	0.37	0.33
26	0.00	--	0.21	0.25	0.00	--	0.16	0.18	0.00	--	0.30	0.30
27	0.00	--	0.15	0.23	4.06	--	0.32	0.43	0.00	--	0.38	0.23
28	0.00	--	0.28	0.18	4.06	--	1.96	0.33	0.25	--	0.40	0.30
29	0.00	--	0.29	0.18	0.00	--	0.97	0.38	0.25	--	0.34	0.28
30	0.00	--	0.27	0.18	0.00	--	0.46	0.36				
31	0.00	--	0.14	0.18	0.00	--	0.50	0.46				
TOT	19.56	--	12.88	6.92	25.38	--	12.94	8.36	35.57	--	16.60	9.44

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	March 1992				April 1992				May 1992			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.25	--	0.28	0.33	0.00	--	1.11	1.73	0.00	--	2.04	1.75
2	0.00	--	0.44	0.20	0.00	--	1.14	2.01	0.00	--	2.54	2.31
3	0.25	--	0.50	0.41	0.00	0.78	0.92	1.30	0.00	--	3.27	2.97
4	0.00	--	0.94	0.46	0.00	0.71	0.63	0.91	0.00	--	3.89	3.25
5	0.00	--	1.11	0.56	0.00	0.73	0.68	0.74	0.00	--	4.31	3.43
6	0.00	--	1.07	0.66	0.00	0.55	0.57	0.84	0.00	--	4.47	3.63
7	0.00	--	1.10	0.69	0.00	0.28	0.30	0.74	0.00	3.78	4.27	3.30
8	1.02	--	1.01	0.89	0.25	--	0.55	1.04	0.00	1.36	1.47	1.42
9	0.00	--	1.55	0.81	7.62	0.33	0.34	0.58	0.00	2.12	2.34	1.93
10	0.00	--	1.09	0.81	0.00	0.92	0.94	1.45	0.00	2.32	2.45	2.01
11	0.00	--	0.90	0.86	1.27	0.50	0.59	1.02	0.00	1.07	1.17	1.60
12	0.00	--	0.92	0.91	1.27	0.79*	0.64	0.97	0.00	1.10	1.12	1.78
13	0.00	--	0.93	0.99	13.46	1.32	1.39	1.55	0.00	1.46	1.59	2.41
14	0.25	--	1.15	1.09	0.25	1.20	1.39	1.27	0.00	--	1.73	2.97
15	0.00	--	0.73	0.84	0.00	0.99	0.99	1.55	0.00	--	1.59	2.72
16	0.76	--	0.59	0.89	1.52	1.34	1.35	1.35	0.00	--	1.56	2.69
17	0.00	--	0.55	0.79	0.00	1.13	1.27	1.14	0.00	--	1.67	3.00
18	0.00	--	0.95	0.86	0.00	1.09	1.13	1.42	0.00	--	1.32	2.64
19	0.00	--	0.71	0.89	0.00	1.14	1.34	1.68	0.00	--	0.95	2.11
20	0.00	--	0.71	0.91	0.00	0.93	1.06	1.37	0.00	--	0.91	1.73
21	0.00	--	0.51	0.89	0.00	0.98	1.07	1.24	0.00	--	1.04	1.91
22	0.00	--	0.56	0.92	0.51	1.03	1.11	1.30	0.00	--	1.05	2.13
23	0.00	--	0.64	1.07	0.00	1.04	1.15	1.37	0.00	--	1.38	2.59
24	0.00	--	0.78	1.22	0.00	0.92	1.03	1.78	0.00	--	1.03	2.82
25	0.00	0.53	0.62	1.12	0.00	1.26	1.46	2.21	TR	--	0.83	2.59
26	0.00	0.45	0.58	0.99	0.00	1.90	2.10	2.39	0.00	--	0.61	1.80
27	0.00	0.65	0.72	1.02	0.00	1.40	1.73	1.88	0.00	--	0.86	1.88
28	0.00	0.43	0.51	0.74	0.00	1.51	1.71	2.01	0.00	--	0.44	1.68
29	0.00	0.46	0.56	0.91	8.13	1.23	1.27	1.70	0.00	0.36	0.42	1.73
30	0.00	--	0.82	1.45	0.25	1.55	1.64	1.45	0.00	0.31	0.32	1.80
31	0.00	--	1.00	1.65					0.00	0.32	0.32	1.75
TOT	2.53	--	24.53	26.83	34.53	--	32.60	41.99	TR	--	52.96	72.33

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	June 1992				July 1992				August 1992			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)	PRC (mm)	BR (mm)	PM (mm)	DPM (mm
1	0.00	0.25	0.26	1.47	0.00	0.37	0.51	0.56	0.00	0.34	0.37	0.31
2	TR	0.63	0.68	1.22	0.00	0.49	0.55	0.56	0.00	0.40	0.42	0.30
3	TR	0.26	0.26	1.02	0.00	0.47	0.56	0.56	0.00	0.23	0.28	0.23
4	0.00	0.18	0.20	0.94	0.00	--	0.38	0.33	0.00	0.32	0.34	0.20
5	0.00	0.25	0.25	0.99	0.25	0.59	0.69	0.64	0.00	0.17	0.23	0.18
6	0.00	0.33	0.37	1.02	0.00	0.63*	0.68	0.38	TR	--	0.19	0.10
7	0.00	0.35	0.36	0.92	0.00	0.41	0.51	0.33	TR	0.62	0.65	0.13
8	0.00	--	0.31	0.91	0.00	0.43	0.49	0.33	0.00	0.36	0.35	0.10
9	0.00	--	0.15	0.58	0.00	0.75	0.72	0.33	0.00	0.23	0.26	0.13
10	0.00	--	0.15	0.64	1.02	--	0.30	1.22	0.00	0.17	0.24	0.13
11	0.25	0.20	0.17	0.97	0.00	0.64	0.66	0.26	0.00	0.15	0.20	0.13
12	24.38	1.01	1.15	1.83	0.00	0.87	0.95	0.31	0.00	0.25	0.31	0.08
13	2.54	--	1.76	1.68	0.00	0.73	0.76	0.28	0.00	0.61	0.65	0.10
14	0.00	--	1.70	1.83	0.00	--	0.46	0.26	0.00	0.62	0.74	0.10
15	0.51	--	1.73	2.31	0.00	0.39	0.43	0.23	0.00	0.65	0.68	0.08
16	0.00	--	1.86	2.36	0.00	0.38	0.40	0.23	0.00	0.24	0.33	0.08
17	0.00	--	1.40	2.24	0.00	0.46	0.50	0.25	0.00	0.25	0.34	0.08
18	0.00	--	1.99	2.62	TR	0.38	0.46	0.20	0.00	0.28	0.33	0.05
19	0.00	--	1.86	2.54	0.00	0.29	0.29	0.15	0.00	0.23	0.28	0.05
20	0.00	--	1.40	2.26	3.30	0.56	0.76	1.65	0.00	0.21	0.24	0.05
21	TR	--	1.50	2.11	0.00	0.67	0.80	0.28	2.54	0.25	0.40	1.52
22	TR	1.33	1.80	1.63	TR	--	0.54	0.15	3.81	0.87	1.18	1.47
23	0.00	2.04	2.21	1.55	5.08	0.74	1.22	1.52	0.00	0.28	0.32	0.18
24	0.00	--	2.16	1.27	0.00	0.65	0.77	0.43	0.00	0.52	0.56	0.20
25	0.00	--	1.42	1.07	TR	0.77	0.75	0.58	0.00	0.51	0.52	0.23
26	0.00	--	0.70	0.79	0.00	0.81	0.81	0.61	0.00	0.47	0.49	0.23
27	0.00	0.53	0.71	0.92	0.00	0.78	0.84	0.58	0.00	0.22	0.26	0.23
28	0.00	0.51	0.71	2.24	0.00	0.54	0.61	0.48	0.00	0.27	0.35	0.20
29	0.25	1.42	1.65	0.69	0.00	0.29	0.35	0.36	0.00	0.15	0.18	0.18
30	0.00	0.56	0.70	0.58	0.00	0.35	0.38	0.41	0.00	0.17	0.19	0.13
31					0.00	0.34	0.38	0.41	0.00	0.22	0.21	0.13
TOT	31.74	--	32.02	43.20	9.65	--	18.51	14.87	6.35	--	12.09	7.31

Table 4.--*Daily and monthly precipitation and evapotranspiration and canopy resistance at the Snively Basin site, May 31, 1990, to September 30, 1992--Continued*

	September 1992			
Day	PRC (mm)	BR (mm)	PM (mm)	DPM (mm)
1	0.00	0.30	0.29	0.15
2	0.00	0.25	0.26	0.15
3	0.00	0.23	0.26	0.13
4	0.00	0.32	0.28	0.08
5	0.00	0.23	0.26	0.08
6	0.00	0.18	0.20	0.05
7	0.00	0.24	0.29	0.08
8	0.00	--	0.41	0.08
9	0.00	0.15	0.20	0.08
10	0.00	0.11	0.16	0.08
11	0.00	--	0.18	0.08
12	0.00	0.19	0.26	0.05
13	0.00	0.23	0.30	0.05
14	0.00	--	0.13	0.31
15	4.32	--	0.53	0.76
16	0.00	--	0.86	0.71
17	0.00	0.26	0.34	0.13
18	0.00	0.26	0.36	0.18
19	0.25	0.22	0.24	0.41
20	0.00	0.19	0.24	0.15
21	0.00	0.34	0.45	0.15
22	0.00	0.25	0.34	0.15
23	3.81	0.81	0.81	1.40
24	1.52	0.72	0.97	1.14
25	0.00	0.31	0.40	0.41
26	0.00	0.45	0.56	0.20
27	0.00	0.26	0.34	0.15
28	0.00	0.22	0.30	0.18
29	0.00	0.24	0.30	0.20
30	0.00	--	0.38	0.20
TOT	9.90	--	10.90	7.97

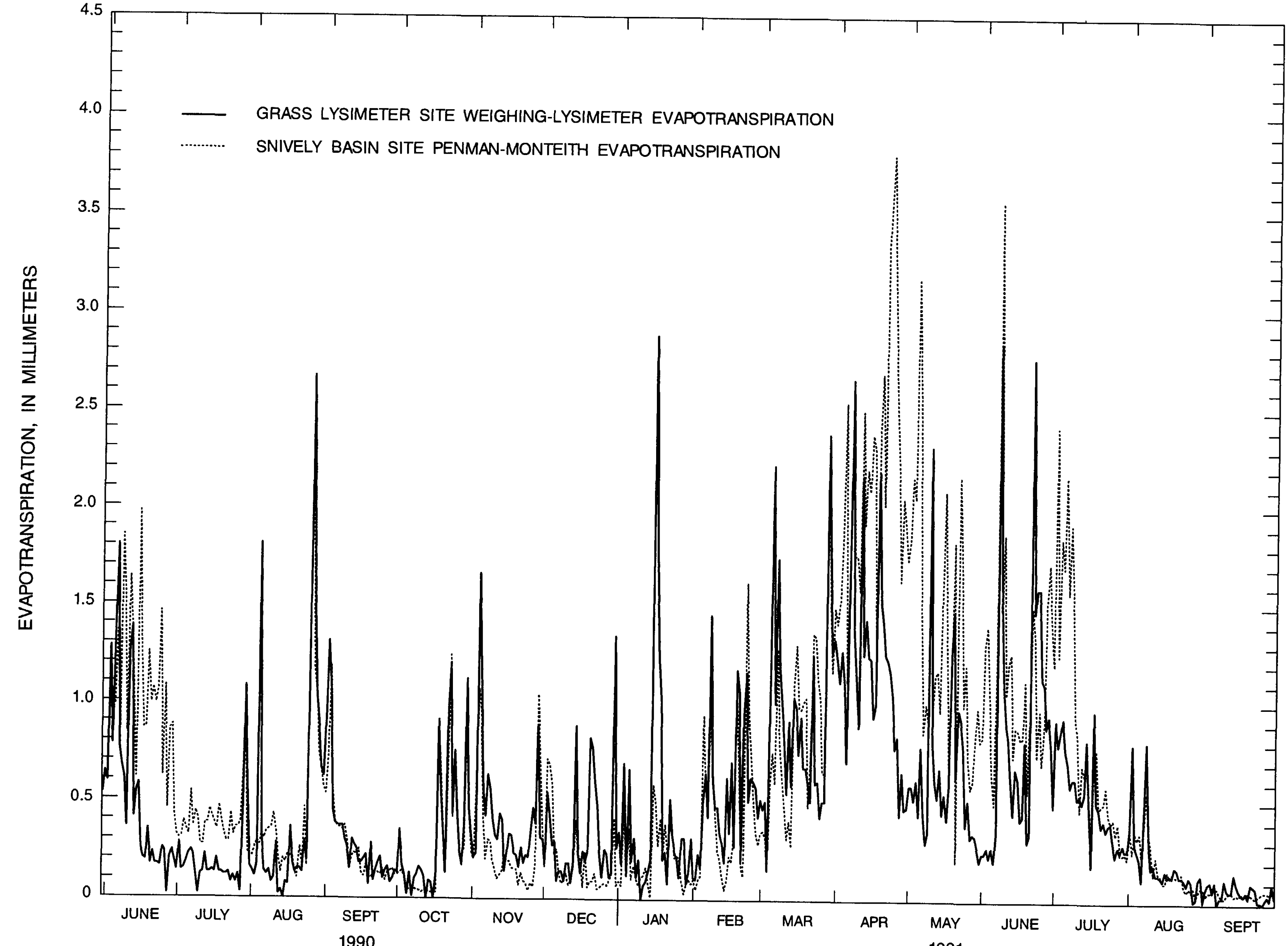

Figure 15.--Daily evapotranspiration at the grass lysimeter site and Snively Basin site, May 30, 1990 to September 30, 1991. Evapotranspiration estimates for the weighing lysimeters at the grass lysimeter site are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

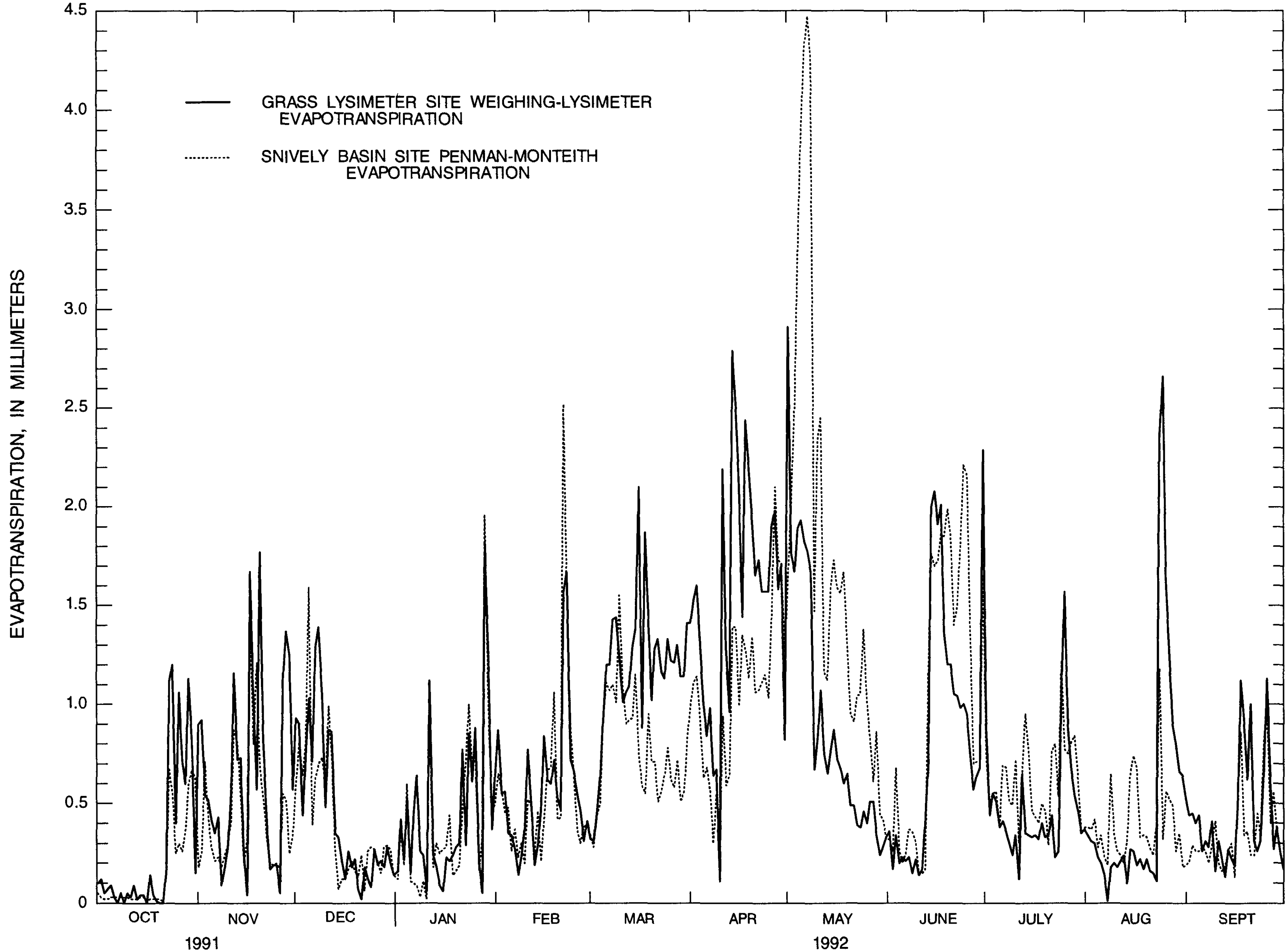

Figure 16.--Daily evapotranspiration at the grass lysimeter site and Snively Basin site, October 1, 1991 to September 30, 1992. Evapotranspiration estimates for the weighing lysimeters at the grass lysimeter site are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

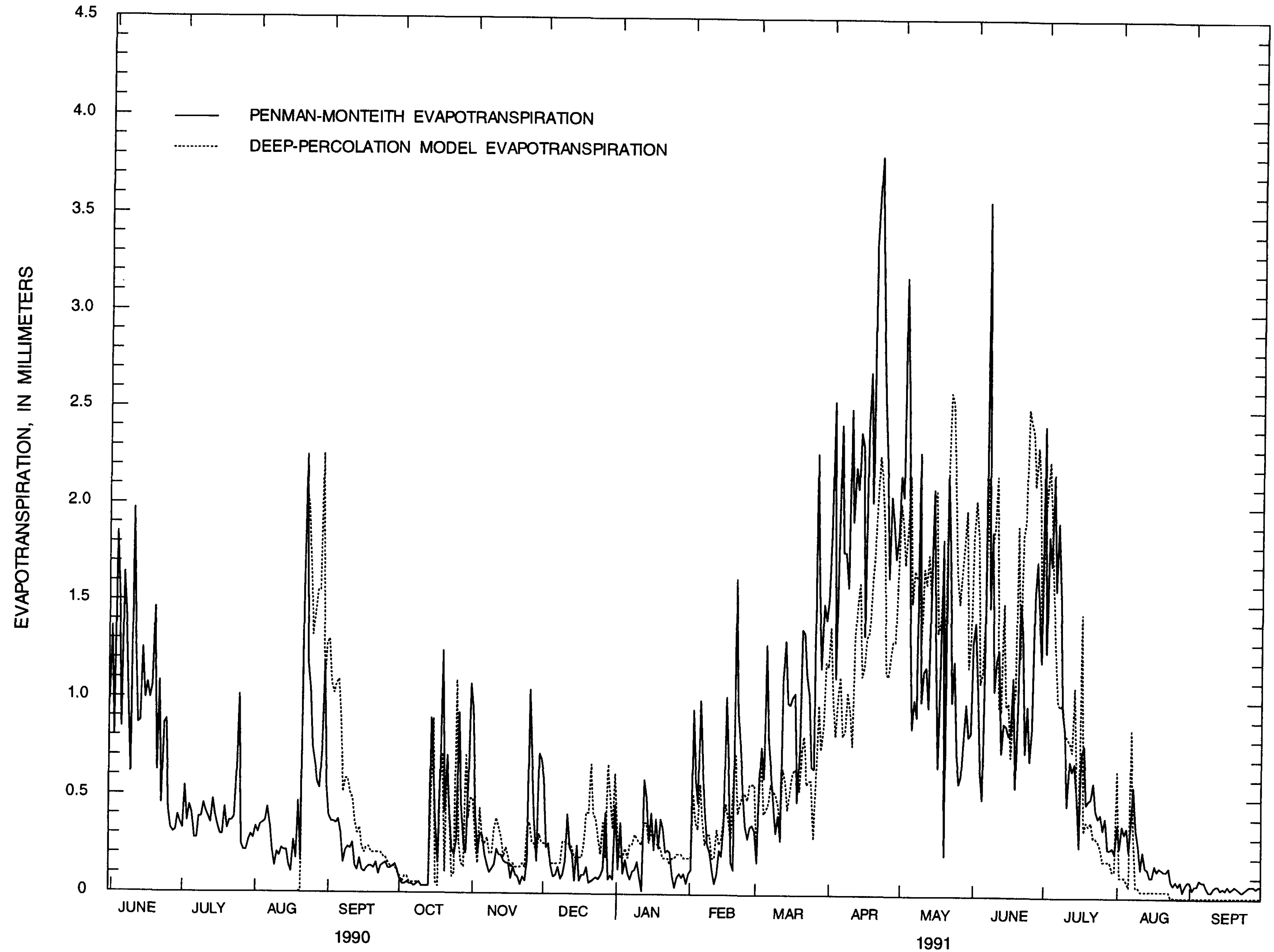

Figure 17.--Daily evapotranspiration at the Snively Basin site from the Penman-Monteith method and deep-percolation model, May 30, 1990 to September 30, 1991.

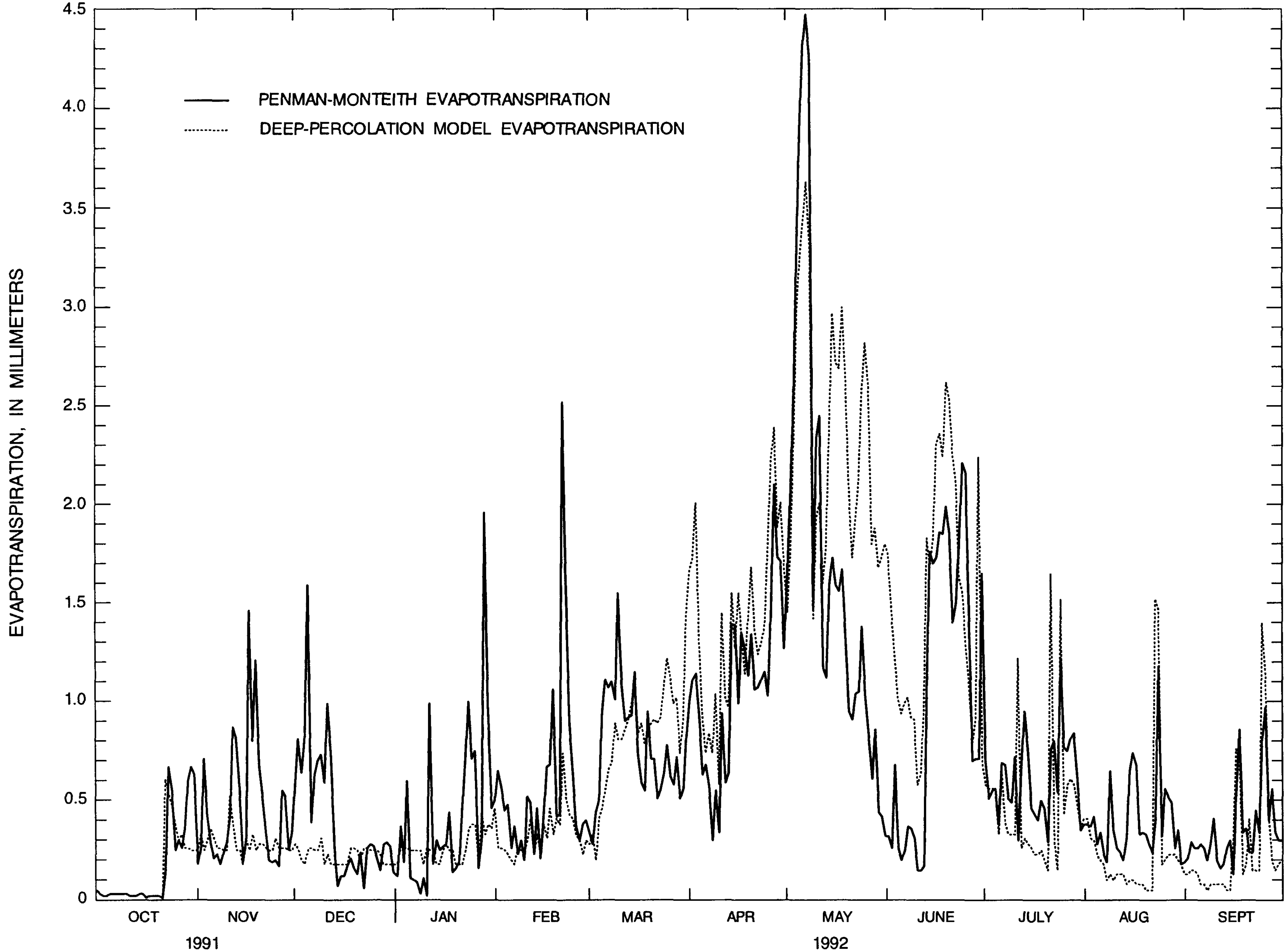

Figure 18.--Daily evapotranspiration at the Snively Basin site from the Penman-Monteith method and the deep-percolation model, October 1, 1991 to September 30, 1992.

From these differences, several months stand out and show some of the major contrasts between the Penman-Monteith and model ET estimates. During late August and in September 1990, the deep-percolation model yielded much higher ET rates than did the Penman-Monteith method (fig. 17). The 28.19 mm rainfall on August 21, 1990, resulted in Penman-Monteith ET of over 1 mm for just 4 days afterwards, with ET decreasing over the next 2 weeks as soils dried (table 4). The model, however, showed ET rates over 1 mm for 16 days after the rainfall. This contrast between methods occurred after another heavy rain in June 1991 and to a lesser extent in June 1992 (table 4, figs. 17-18). These differences probably occur because the model's plant growth curve doesn't account for the fact that plants at the Snively Basin site are usually not actively growing in summer. Thus, the model may overestimate plant transpiration after summer rainfalls when most of the ET is actually due to soil evaporation.

During December 1990 and in August, September, and October 1991, model ET was much more or less than Penman-Monteith ET, primarily due to the very small ET values involved. During these months, daily Penman-Monteith ET was mostly under 0.2 mm. Thus, small errors of any kind in the Penman-Monteith data or the model inputs could produce large percentages of difference. Also, the model accounted for all input precipitation by August 23, 1991, in the model simulation, so zero ET was estimated by the model from then to October 21, 1991. Penman-Monteith ET (table 4) and grass lysimeter site ET (table 3) show that ET was rarely zero, even under the driest or coldest of conditions, though it may have closely approached it.

Another difference between Penman-Monteith and model ET estimates is in ET from April to June. The Penman-Monteith estimates show large bursts of ET at certain times (April 2-26, 1991 and May 1-10, 1992) when the model shows as much as 50 percent less ET. Later in spring (May 22 to June 4, 1991 and May 14 to June 11, 1992), the model estimates much more ET than the Penman-Monteith estimates (table 4, figs. 17-18). These contrasts may be due to differences between the plant growth curve used by the model and the actual growth of the grasses at the Snively Basin site. The grasses may exhibit bursts of transpiration under favorable spring conditions, then greatly lower their transpiration rate as they begin senescing when the available water is nearly used up. The transition may take only 2 to 4 weeks, as shown from May to June in 1991 and 1992 (table 4). The model's growth curve does not incorporate this characteristic, so the model partitions the ET at more uniform rates over a longer period of time.

The average of the seasonal differences between Penman-Monteith ET and model ET was only 0.7 percent, but varied seasonally:

	1990	1991	1992
Winter	--	-23.6	-17.5
Spring	--	.3	34.0
Summer	88.1	-20.7	-27.4
Fall	5.9	-45.0	--

For the above table, summer is defined as the months of July to September, fall is October to December, winter is January to March, and spring is April to June.

Compared with daily Penman-Monteith ET, daily model ET was less during winter, summer, and fall and higher in the spring. For summer and fall of 1990, the values reflect ET after a rare heavy summer thunderstorm and are not typical of the usually dry summers (1991 and 1992) and fall (1991). The remaining seasonal variabilities could be caused by (1) the model not incorporating wind speed, which can be an important factor in estimating ET with some methods, and (2) errors in the collected data or variable inputs used in the model, particularly for small ET values.

Turnbull Meadow and Marsh Sites

Seasonal patterns of ET at the Turnbull meadow and marsh sites were similar except during mid-summer to fall, when the marsh site showed two to three times the ET of the meadow site (table 5, fig. 19). During this period in 1991, the soils at the marsh site were twice as moist as soils at the meadow site, in part because of 20 percent higher rainfall during the summer at the marsh site but perhaps also because of location. Sixty-four percent of this higher rainfall was due to a June 28, 1991 thunderstorm that produced 16 mm of rainfall at the marsh site but none at the meadow site. The marsh site is in an area of ground-water discharge, which would contribute to moister soils than at the meadow site. Also, the marsh site may have received runoff from adjacent upland areas in winter and spring.

At the Turnbull meadow site from May to October 1991, latent-heat flux and ET (fig. 11, table 5) estimated with the Bowen-ratio method agreed well with ET estimated with the Penman-Monteith method (table 5). The r^2 of the two methods was 0.96 (Tomlinson, 1995). This close correlation was due almost entirely to the agreement of the average daily canopy resistance with the canopy resistance measured for each daily 20-minute interval. Because the Bowen-ratio method was used to calibrate the Penman-Monteith equation for canopy resistance, close estimates of ET from the two methods were expected.

Turnbull meadow site ET from mid-October 1991 to September 1992 was determined only with the Penman-Monteith method. Daily canopy resistances for the Penman-Monteith method derived from a soil moisture-canopy resistance relation developed from Bowen- ratio measurements from 1991 (Tomlinson, 1995). No Bowen-ratio measurements were made at the Turnbull meadow site in 1992. To estimate ET in 1992 with the Penman-Monteith method, it was assumed that the soil moisture-canopy resistance relation for 1992 was the same as for 1991 (table 5, fig. 19).

The meadow site soil moisture-canopy resistance relation was also used at the marsh site to determine Penman-Monteith ET because of similar site conditions (Tomlinson, 1995). Vegetation, canopy height, topography, net radiation, relative humidity, and soil-heat flux—all variables that can affect canopy resistance—were nearly the same at the meadow and marsh sites. Though these similarities suggest the soil moisture-canopy resistance relation was the same at both sites, it is possible the relation was different for each. If this relation was in error or did not apply at the marsh site, then the ET estimates for the marsh site might vary from those shown. This error is unquantifiable because no Bowen-ratio data were collected at the marsh site to verify the relation.

Black Rock Valley Site

For the Black Rock Valley site, comparisons of Bowen-ratio and Penman-Monteith latent-heat fluxes and ET showed close agreement. The r^2 for the daily estimates of Bowen-ratio and Penman-Monteith ET was 0.91. This good correlation was expected because the Bowen-ratio method was used to calibrate the Penman-Monteith method. However, there were some cases where the ET estimates of the two methods did not agree well (table 6). For instance, from July 26-28, 1992, Penman-Monteith ET averaged 44 percent higher than Bowen-ratio ET (table 6). The periods of biggest difference in latent-heat flux and ET between the two methods appeared to be during high winds at night such as July 26-28, 1992 (fig. 20). During such periods, the Bowen-ratio method showed little latent-heat flux, while the Penman-Monteith method showed high latent-heat flux.

During the summer, the Black Rock Valley site is subject to diurnal wind patterns because of its location. During the day, upslope wind speeds of 1 to 3 m/s prevailed, while at night, downslope wind speeds were 7 to 9 m/s (fig. 20). The higher wind speeds at night were probably due to the channeling effect of the topography around the site.

The Penman-Monteith method seems to be more sensitive to high wind speeds at night than the Bowen-ratio method, though both methods take turbulent theory into account. This same pattern was noticed at the Snively Basin site (Tomlinson, 1995). Also, weighing lysimeters showed high ET at night during periods of high wind speeds at the grass lysimeter site, while the Bowen-ratio method showed little ET (Tomlinson, 1995).

(Text continued on p. 73.)

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992*

[mm, millimeters; PRC, precipitation, Turnbull meadow site; BR, evapotranspiration, Bowen-ratio method, Turnbull meadow site; PM1, evapotranspiration, Penman-Monteith method, Turnbull meadow site; PM2, evapotranspiration, Penman-Monteith method, Turnbull marsh site; TOT, monthly totals of daily precipitation and evapotranspiration; TR, data suggests trace of precipitation; *, estimated or partly estimated; --, insufficient data to calculate daily or monthly value]

	May 1991				June 1991				July 1991			
Day	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm
1	--	--	--	--	0.00	4.01	4.02	5.24	0.00	4.41*	4.59	5.69
2	--	--	--	--	0.00	4.00	3.67	6.72	0.00	4.76*	4.84	6.39
3	--	--	--	--	0.00	2.46	2.50	5.82	0.00	5.73*	5.13	7.21
4	--	--	--	--	0.00	3.22	3.87	4.77	0.00	5.05*	5.30	8.73
5	--	--	--	--	0.25	1.74	2.51	3.31	0.00	3.53*	4.20	7.70
6	--	--	--	--	5.08	3.60	3.51	3.70	0.00	3.87*	3.24	5.90
7	--	--	--	--	6.60	2.09	2.43	1.82	0.00	4.03*	4.16	5.25
8	--	--	--	--	0.00	2.24	2.17	2.67	0.00	3.51*	3.96	5.65
9	--	--	--	--	0.00	4.18	4.26	4.37	0.25	4.05*	4.23	5.09
10	--	--	--	--	0.00	5.34	5.37	5.84	0.00	4.42*	3.86	4.86
11	--	--	--	--	1.02	3.87	4.15	6.23	0.00	3.50	3.75	5.30
12	--	--	--	--	0.00	2.37	2.45	3.56	0.00	3.92	4.21	5.92
13	--	--	--	--	0.25	2.21	2.44	2.71	1.52	3.62	4.01	7.00
14	--	--	--	--	0.00	2.45	2.55	3.31	0.00	2.13	2.33	3.98
15	--	--	--	--	0.00	2.90	3.19	3.87	0.00	1.79	1.82	4.18
16	0.76	1.56	1.96	2.17	0.00	2.40	2.43	3.77	0.51	1.41	1.58	1.40
17	10.16	1.01	1.25	1.74	0.00	3.15	2.86	3.29	1.78	1.83	2.12	2.33
18	0.00	1.42	1.26	1.35	0.00	4.22	4.29	4.44	0.00	2.47	2.56	4.45
19	0.00	1.96	2.07	2.61	3.56	2.47	2.82	2.94	0.00	2.00	2.21	4.64
20	0.00	3.21	3.25	5.57	1.27	1.09	1.38	1.08	0.00	1.84	2.14	4.70
21	0.00	2.58	2.49	4.17	0.51	2.33	2.45	2.11	0.00	1.53	1.82	3.64
22	0.00	3.03	3.34	5.27	0.00	2.87	2.44	3.02	0.00	2.02	2.15	4.22
23	0.00	2.97	3.06	4.72	0.00	2.61	2.15	4.02	0.00	1.84	2.06	4.51
24	0.00	1.84	2.15	2.95	4.32	2.96	2.92	2.45	0.25	1.81	1.87	4.12
25	0.51	1.50	1.68	2.87	0.25	2.32	2.42	3.09	3.81	1.97	2.22	2.43
26	0.00	2.22	1.94	3.20	0.00	3.28	3.23	4.45	0.00	1.56	1.72	2.80
27	1.52	2.62	2.28	3.43	0.00	4.53	4.52	5.20	0.00	1.15	1.28	2.91
28	0.00	3.12	3.37	4.03	0.00	3.46	3.43	4.02	0.00	1.12	1.23	2.99
29	0.00	3.36	3.27	4.39	15.24	1.75	1.62	2.04	0.00	0.91	0.83	3.21
30	1.52	1.53	1.72	1.77	0.00	2.60	2.54	3.81	0.00	0.94	1.09	2.93
31	0.00	3.01	3.16	4.40					0.00	1.20	1.31	3.78
TOT	13.96	36.84	38.23	54.64	38.35	88.72	90.59	113.67	8.12	83.92	87.82	143.91

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992--Continued*

	August 1991				September 1991				October 1991			
Day	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm
1	1.78	1.79	2.23	3.36	0.00	0.23	0.23	0.93	0.00	--	0.23	1.02
2	0.00	1.44	1.39	3.72	0.00	0.16*	0.19	1.00	0.00	0.26	0.29	0.80
3	0.00	1.25	1.16	4.00	0.00	0.22*	0.22	1.15	0.00	0.28	0.33	0.74
4	0.00	1.13	1.15	3.82	0.00	0.19*	0.20	1.34	0.00	0.22	0.25	0.71
5	TR	0.75	0.82	0.96	0.00	0.27*	0.29	1.43	0.00	0.26	0.22	0.80
6	9.40	0.98	1.24	2.73	0.00	0.24*	0.25	1.41	0.00	0.28	0.26	0.76
7	TR	1.89	1.80	3.13	0.00	0.41	0.47	0.73	0.00	0.40	0.38	0.66
8	0.00	1.86	1.83	4.40	7.11	1.29*	1.37	0.68	0.00	--	0.30	0.73
9	0.00	1.02	1.11	3.92	0.00	0.52*	0.50	2.14	0.00	--	0.30	0.84
10	TR	1.06	1.19	2.00	0.00	0.57*	0.61	2.51	0.00	--	0.31	0.98
11	0.00	0.83	0.86	2.48	0.00	0.28*	0.30	2.28	0.00	--	0.32	0.97
12	0.76	0.84	0.79	3.39	0.00	0.31*	0.31	2.48	0.00	--	0.38	0.77
13	0.00	0.78	0.67	2.15	TR	0.65	0.64	1.53	0.00	--	0.38	0.77
14	0.00	1.05	1.09	2.14	0.00	0.40*	0.40	1.67	0.00	--	0.41	0.81
15	0.00	1.28	1.28	2.92	0.00	0.34*	0.40	1.75	0.00	--	0.43	0.87
16	0.00	1.23	1.38	3.09	0.00	0.42*	0.52	1.93	0.00	--	0.28	0.65
17	0.00	1.12	1.30	3.39	0.00	0.40*	0.31	1.55	0.00	--	0.15	0.34
18	0.00	1.32	1.43	2.82	0.00	0.24*	0.29	1.56	0.00	--	0.19	0.38
19	0.00	0.84	1.06	2.68	0.00	0.27*	.31	1.70	0.00	--	0.28	0.57
20	0.00	0.86	1.03	2.41	0.00	0.56*	0.65	1.33	0.00	--	0.20	0.45
21	0.00	0.84	0.75	2.41	0.00	0.32*	0.29	0.96	0.00	--	0.15	0.35
22	0.00	0.73	0.85	2.23	0.00	0.61*	0.50	0.94	0.00	--	0.11	0.24
23	0.00	0.75	0.85	1.55	0.00	--	0.47	1.04	0.00	--	0.04	0.10
24	0.00	0.58	0.66	1.51	0.00	--	0.32	1.17	8.89	--	0.04	0.08
25	0.00	0.67	0.66	1.13	0.00	--	0.26	1.21	1.27	--	0.13	0.36
26	0.00	0.73	0.83	1.42	0.00	--	0.25	1.30	3.05	--	0.07	0.15
27	0.00	0.38*	0.45	1.03	0.00	--	0.25	1.36	0.76	--	0.08	0.16
28	TR	0.69	0.64	0.85	0.00	--	0.12	0.99	0.00	--	0.14	0.28
29	0.00	0.87	0.86	1.56	0.00	--	0.18	1.13	0.00	--	0.14	0.32
30	0.00	0.79	0.84	1.81	0.00	--	0.15	1.20	0.00	--	0.07	0.20
31	0.00	0.41*	0.46	1.43					0.00	--	0.08	0.17
TOT	12.19	30.76	32.66	76.44	7.11	--	11.25	42.40	13.97	--	6.94	17.03

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992--Continued*

	November 1991				December 1991				January 1992			
Day	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm
1	0.25	--	0.21	0.50	0.00	--	0.38	0.33	0.25	--	0.51	0.47
2	0.00	--	0.16	0.37	0.00	--	0.88	0.91	7.37	--	0.52	0.32
3	0.00	--	0.16	0.38	0.00	--	0.39	0.33	0.25	--	0.59	0.45
4	5.84	--	0.10	0.19	0.51	--	0.47	0.37	6.86	--	0.62	0.35
5	10.67	--	0.15	0.19	13.21	--	0.53	0.31	0.51	--	0.53	0.40
6	0.00	--	0.25	0.32	7.62	--	0.65	0.44	0.00	--	0.27	0.29
7	0.00	--	0.30	0.37	0.00	--	0.68	0.55	0.25	--	0.42	0.28
8	2.03	--	0.28	0.43	0.00	--	0.63	0.40	0.00	--	0.42	0.51
9	0.00	--	0.23	0.34	0.00	--	1.21	1.05	0.00	--	0.60	0.52
10	1.52	--	0.26	0.31	0.00	--	0.76	0.64	0.51	--	0.80	0.62
11	1.52	--	0.32	0.38	0.00	--	1.23	1.14	2.54	--	0.50	0.33
12	0.51	--	0.50	0.71	1.52	--	1.12	1.17	0.00	--	0.34	0.22
13	0.00	--	0.53	0.88	0.00	--	0.80	0.70	0.00	--	0.49	0.35
14	0.00	--	0.30	0.43	0.00	--	0.61	0.49	0.00	--	0.36	0.28
15	0.00	--	0.23	0.39	0.00	--	0.48	0.40	0.00	--	0.54	0.45
16	10.16	--	0.36	0.54	0.00	--	0.40	0.28	5.82	--	0.50	0.34
17	2.54	--	0.90	0.66	0.00	--	0.52	0.45	0.00	--	0.41	0.29
18	0.00	--	0.41	0.44	5.59	--	0.41	0.29	0.00	--	0.60	0.43
19	5.59	--	0.55	0.48	0.00	--	0.19	0.20	0.00	--	0.42	0.32
20	6.60	--	0.79	0.68	1.52	--	0.41	0.35	0.00	--	0.44	0.31
21	0.00	--	0.58	0.47	0.00	--	0.80	0.52	2.54	--	0.57	0.41
22	0.51	--	0.38	0.34	5.59	--	0.38	0.27	2.54	--	0.86	0.66
23	0.00	--	0.32	0.23	0.25	--	0.35	0.36	12.45	--	0.84	0.52
24	6.60	--	0.27	0.21	0.00	--	0.32	0.37	0.00	--	1.03	0.69
25	8.64	--	0.33	0.28	0.00	--	0.57	0.57	0.00	--	1.25	0.97
26	8.38	--	0.33	0.27	0.00	--	0.64	0.53	0.00	--	0.79	0.65
27	7.37	--	0.37	0.27	0.00	--	0.79	0.59	15.75	--	0.95	0.48
28	1.78	--	0.50	0.32	0.00	--	0.57	0.56	4.32	--	1.74	0.99
29	1.02	--	0.80	0.78	0.00	--	0.71	0.66	3.56	--	1.01	0.38
30	0.00	--	0.49	0.44	0.00	--	0.47	0.35	0.00	--	1.66	0.84
31					0.00	--	0.65	0.53	0.00	--	3.92	1.92
TOT	81.53	--	11.36	12.60	35.81	--	19.00	16.11	61.46	--	24.50	16.04

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992--Continued*

Day	February 1992				March 1992				April 1992			
	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm
1	0.00	--	1.37	0.97	1.78	--	1.57	1.17	0.00	--	3.67	3.21
2	0.00	--	1.47	1.13	0.00	--	2.00	1.62	0.00	--	4.22	3.76
3	0.00	--	1.62	1.33	0.51	--	0.90	0.68	0.00	--	2.58	2.48
4	0.00	--	1.35	1.11	0.00	--	1.31	1.05	0.00	--	2.28	2.43
5	0.00	--	1.24	1.01	0.00	--	2.22	1.88	0.00	--	1.52	1.67
6	0.25	--	1.28	1.07	0.00	--	1.99	1.77	0.25	--	1.16	1.26
7	2.03	--	1.05	1.05	1.52	--	1.25	1.08	0.00	--	1.39	1.31
8	1.27	--	0.40	0.32	0.25	--	2.28	2.10	0.00	--	1.99	1.95
9	4.32	--	0.66	0.44	0.00	--	2.42	2.21	6.35	--	.56	.51
10	0.00	--	1.26	1.16	0.00	--	2.39	2.19	0.25	--	1.89	1.92
11	0.25	--	1.69	1.15	0.00	--	2.51	2.30	0.25	--	1.49	1.58
12	0.00	--	1.47	1.15	0.00	--	2.82	2.49	2.79	--	1.10	1.07
13	1.52	--	1.25	1.06	0.00	--	3.52	3.05	4.57	--	1.44	1.75
14	0.25	--	1.60	1.23	0.00	--	3.24	2.81	0.00	--	2.85	2.74
15	0.51	--	0.59	0.44	0.51	--	1.49	1.26	0.00	--	3.51	3.63
16	0.00	--	1.31	1.16	0.51	--	2.19	1.80	3.56	--	1.52	1.67
17	2.29	--	0.95	0.68	7.62	--	1.11	1.01	2.54	--	2.24	3.24
18	23.88	--	0.79	0.46	0.00	--	1.71	1.39	0.00	--	2.85	4.00
19	0.51	--	1.45	1.21	0.00	--	2.14	1.92	0.00	--	3.10	3.52
20	17.78	--	0.81	0.62	0.00	--	3.03	2.67	0.00	--	2.93	3.89
21	1.27	--	1.38	0.80	0.00	--	2.89	2.66	0.00	--	2.17	2.83
22	0.00	--	2.35	2.35	0.00	--	2.82	2.56	0.00	--	1.95	2.91
23	2.54	--	1.42	1.16	0.00	--	2.77	2.49	0.00	--	2.49	3.26
24	3.05	--	0.51	0.33	0.00	--	2.84	2.58	0.00	--	3.64	4.58
25	0.00	--	0.93	0.74	0.00	--	3.17	2.74	0.00	--	4.92	5.31
26	0.00	--	0.96	0.75	0.00	--	2.37	2.16	0.00	--	4.82	5.32
27	0.00	--	0.79	0.64	0.00	--	2.26	2.34	0.00	--	3.34	4.49
28	0.00	--	0.68	0.55	0.00	--	2.85	2.52	0.00	--	2.45	2.97
29	0.00	--	0.69	0.55	0.00	--	2.71	2.27	2.54	--	1.70	1.92*
30					0.00	--	3.48	3.16	3.05	--	2.88	3.26*
31					0.00	--	3.28	2.86				
TOT	60.45	--	33.32	26.39	12.70	--	73.53	64.79	26.15	--	74.65	84.44*

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992--Continued*

	May 1992				June 1992				July 1992			
Day	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm)	PRC (mm)	BR (mm)	PM1 (mm)	PM2 (mm
1	0.00	--	2.83	--	0.00	--	2.19	--	2.54	--	1.13	--
2	0.00	--	2.97	--	0.00	--	1.39	--	0.00	--	0.86	--
3	0.00	--	4.53	--	0.00	--	1.43	--	0.25	--	1.04	--
4	0.00	--	4.94	--	0.00	--	1.03	--	0.00	--	0.70	--
5	0.00	--	5.14	--	0.00	--	1.08	--	0.00	--	0.67	--
6	0.00	--	5.60	--	0.00	--	1.10	--	0.00	--	0.54	--
7	0.00	--	5.40	--	0.00	--	0.91	--	0.00	--	0.31	--
8	0.00	--	2.31	--	0.00	--	0.88	--	0.00	--	0.32	--
9	0.00	--	1.92	--	0.00	--	0.67	--	0.00	--	0.32	--
10	0.00	--	2.20	--	0.00	--	0.80	--	0.25	--	0.16	--
11	0.00	--	1.71	--	0.00	--	0.53	--	0.00	--	0.21	--
12	0.00	--	1.95	--	10.92	--	0.21	--	0.00	--	0.24	--
13	0.00	--	2.46	--	9.40	--	0.85	--	0.00	--	0.23	--
14	0.00	--	2.63	--	0.00	--	0.90	--	0.00	--	0.23	--
15	0.00	--	2.21	--	0.51	--	1.45	--	0.00	--	0.23	--
16	0.00	--	2.09	--	0.76	--	1.21	--	0.00	--	0.30	--
17	0.00	--	2.30	--	1.27	--	2.42	--	0.00	--	0.39	--
18	0.00	--	2.05	--	0.00	--	3.16	--	0.00	--	0.38	--
19	0.00	--	1.59	--	0.00	--	3.35	--	0.51	--	0.31	--
20	0.00	--	0.96	--	0.00	--	2.88	--	1.02	--	0.27	--
21	0.00	--	1.08	--	0.00	--	3.04	--	1.02	--	0.30	--
22	0.00	--	1.27	--	0.00	--	2.89	--	2.79	--	0.16	--
23	0.00	--	1.55	--	0.00	--	2.80	--	1.27	--	0.14	--
24	0.00	--	1.48	--	0.00	--	2.48	--	0.25	--	0.40	--
25	0.00	--	1.59	--	0.00	--	1.97	--	0.00	--	1.05	--
26	4.57	--	1.25	--	0.00	--	1.33	--	0.00	--	1.06	--
27	0.00	--	1.73	--	0.00	--	1.71	--	0.00	--	1.10	--
28	0.00	--	1.67	--	0.00	--	1.20	--	0.00	--	1.03	--
29	0.00	--	1.61	--	4.32	--	0.92	--	0.00	--	1.12	--
30	0.00	--	2.00	--	0.00	--	1.00	--	0.00	--	1.25	--
31	0.00	--	2.10	--					0.00	--	1.50	--
TOT	4.57	--	75.12	--	12.70	--	47.78	--	9.90	--	17.95	--

Table 5.--*Daily and monthly precipitation and evapotranspiration at the Turnbull meadow and marsh sites, May 16, 1991, to September 30, 1992--Continued*

Day	August 1992 PRC (mm)	August 1992 BR (mm)	August 1992 PM1 (mm)	August 1992 PM2 (mm)	September 1992 PRC (mm)	September 1992 BR (mm)	September 1992 PM1 (mm)	September 1992 PM2 (mm)
1	0.00	--	1.27	--	0.00	--	1.06	--
2	0.00	--	1.05	--	0.00	--	1.11	--
3	0.00	--	1.01	--	0.00	--	1.18	--
4	0.00	--	0.89	--	0.00	--	0.73	--
5	0.00	--	0.64	--	0.00	--	0.70	--
6	0.00	--	0.48	--	0.00	--	0.62	--
7	0.00	--	0.39	--	0.00	--	0.70	--
8	0.00	--	0.45	--	2.29	--	0.98	--
9	0.00	--	0.55	--	0.00	--	1.17	--
10	0.00	--	0.73	--	0.00	--	1.25	--
11	0.00	--	0.86	--	0.00	--	0.98	--
12	0.00	--	0.90	--	0.00	--	0.82	--
13	0.00	--	1.04	--	0.00	--	0.55	--
14	0.00	--	0.98	--	4.57	--	0.47	--
15	0.00	--	0.86	--	0.51	--	0.36	--
16	0.00	--	0.89	--	0.00	--	0.44	--
17	0.00	--	0.89	--	0.00	--	0.94	--
18	0.00	--	0.93	--	0.00	--	1.07	--
19	0.00	--	0.81	--	0.00	--	0.93	--
20	0.00	--	0.65	--	0.00	--	0.76	--
21	0.25	--	0.36	--	0.00	--	0.93	--
22	12.19	--	0.47	--	0.00	--	1.21	--
23	0.00	--	0.90	--	3.81	--	0.79	--
24	0.00	--	1.12	--	3.30	--	0.54	--
25	0.00	--	1.36	--	0.00	--	1.02	--
26	0.00	--	1.55	--	0.00	--	0.95	--
27	0.00	--	1.48	--	0.00	--	1.24	--
28	0.00	--	1.40	--	0.00	--	1.45	--
29	0.00	--	1.36	--	0.00	--	1.45*	--
30	0.00	--	1.50	--	0.00	--	1.46*	--
31	0.00	--	1.27	--				
TOT	12.44	--	29.04	--	14.48	--	27.86*	--

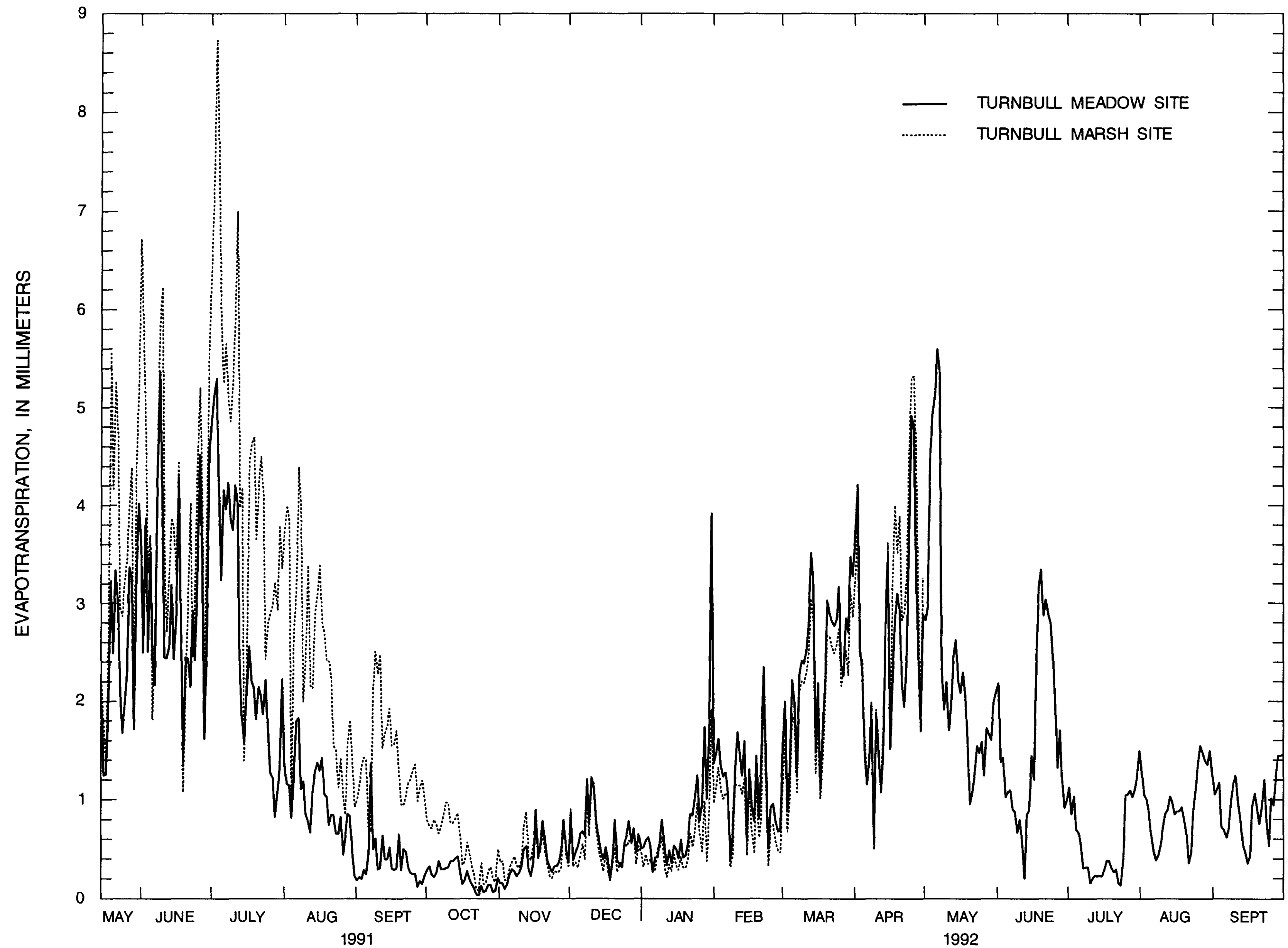

Figure 19.--Daily evapotranspiration at the Turnbull meadow and marsh sites, May 15, 1991 to September 30, 1992.

Table 6.--*Daily and monthly precipitation and evapotranspiration for Black Rock Valley site, March 27 to September 30, 1992*

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

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

Table 6.--*Daily and monthly precipitation and evapotranspiration for Black Rock Valley site, March 27 to September 30, 1992--Continued*

	June 1992			July 1992			August 1992		
Day	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)	PRC (mm)	BR (mm)	PM (mm)
1	TR	0.98	0.93	TR	1.61	1.68	0.00	--	1.59
2	0.00	--	1.17	0.00	2.58	2.93	0.00	--	1.65
3	0.00	--	0.56	0.00	2.26	2.80	0.00	--	1.26
4	0.00	--	0.77	1.78	3.11	3.47	0.00	0.93	0.90
5	0.00	--	0.74	0.00	2.55	2.31	TR	0.65	0.77
6	0.00	1.28	1.49	TR	1.80	2.03	TR	1.00	1.09
7	0.00	1.05	0.98	TR	1.86	2.14	0.00	0.64	0.74
8	0.00	1.05	0.96	0.00	1.42	1.96	0.00	0.69	0.73
9	0.00	0.73	0.70	0.00	1.57	2.09	0.00	0.68	0.77
10	0.00	1.16	1.19	TR	1.99	1.50	0.00	--	0.95
11	0.00	1.54	1.71	0.00	1.25	1.53	0.00	--	0.90
12 1	1.18	--	1.93	0.00	2.49	2.85	0.00	--	0.71
13	0.76	--	1.17	0.51	2.06	1.83	0.00	--	0.70
14	0.00	--	0.95	0.00	2.13	2.77	0.00	0.66	0.80
15	0.00	--	1.45	0.00	1.77	2.25	0.00	0.50	0.65
16	0.00	--	1.86	0.00	1.64	2.10	0.00	--	0.78
17	0.00	1.05*	1.16	0.00	--	2.40	0.00	0.51	0.51
18	0.00	1.65	1.82	TR	--	1.67	0.00	0.58	0.69
19	0.00	2.37	2.86	0.25	0.66	0.84	0.00	0.50	0.49
20	0.00	1.12	1.08	0.00	0.59*	0.90	0.00	--	0.47
21	0.00	1.64	1.79	0.00	1.94	2.13	2.79	--	0.82
22	0.00	--	2.13	0.76	0.71*	0.74	3.56	2.04	2.04
23	0.00	--	1.91	31.50	3.26	2.73	0.00	1.10	1.15
24	0.00	--	1.84	0.00	2.41	2.69	0.00	0.82	0.80
25	0.00	1.50	1.70	0.00	3.12	3.58	0.00	0.82	0.87
26	0.00	0.98*	1.10	0.00	3.13	3.90	0.00	0.54	0.58
27	TR	1.84	2.33	0.00	2.38	3.68	0.00	0.55	0.60
28	7.87	1.43	1.64	0.00	1.71	2.82	0.00	0.63	0.63
29	0.25	2.20	2.31	0.00	--	1.47	0.00	0.58	0.78
30	0.51	2.12	2.34	0.00	--	1.49	0.00	0.52	0.51
31	0.00	--	1.44	0.00	0.52	0.62			
TOT	20.57	--	44.57	34.29	--	68.72	6.60	--	26.55

Table 6.--*Daily and monthly precipitation and evapotranspiration for Black Rock Valley site, March 27 to September 30, 1992--Continued*

	September 1992		
Day	PRC (mm)	BR (mm)	PM (mm)
1	0.00	--	0.59
2	0.00	--	0.69
3	0.00	--	0.72
4	0.00	--	0.33
5	0.00	--	0.41
6	0.00	--	0.26
7	0.00	--	0.29
8	TR	--	0.25
9	0.00	--	0.44
10	0.00	--	0.46
11	0.00	--	0.27
12	0.00	--	0.16
13	0.00	--	0.16
14	0.25	--	0.14
15	6.10	--	1.01
16	0.00	--	1.54
17	0.00	--	1.37
18	0.00	--	0.97
19	0.51	--	1.76
20	0.00	--	0.61
21	0.00	--	0.97
22	0.00	--	0.64
23	0.25	--	0.36
24	2.54	--	1.15
25	0.00	--	0.50
26	0.00	--	0.27
27	0.00	--	0.27
28	0.00	--	0.34
29	0.00	--	0.31
30	0.00	--	0.37
TOT	9.65	--	17.61

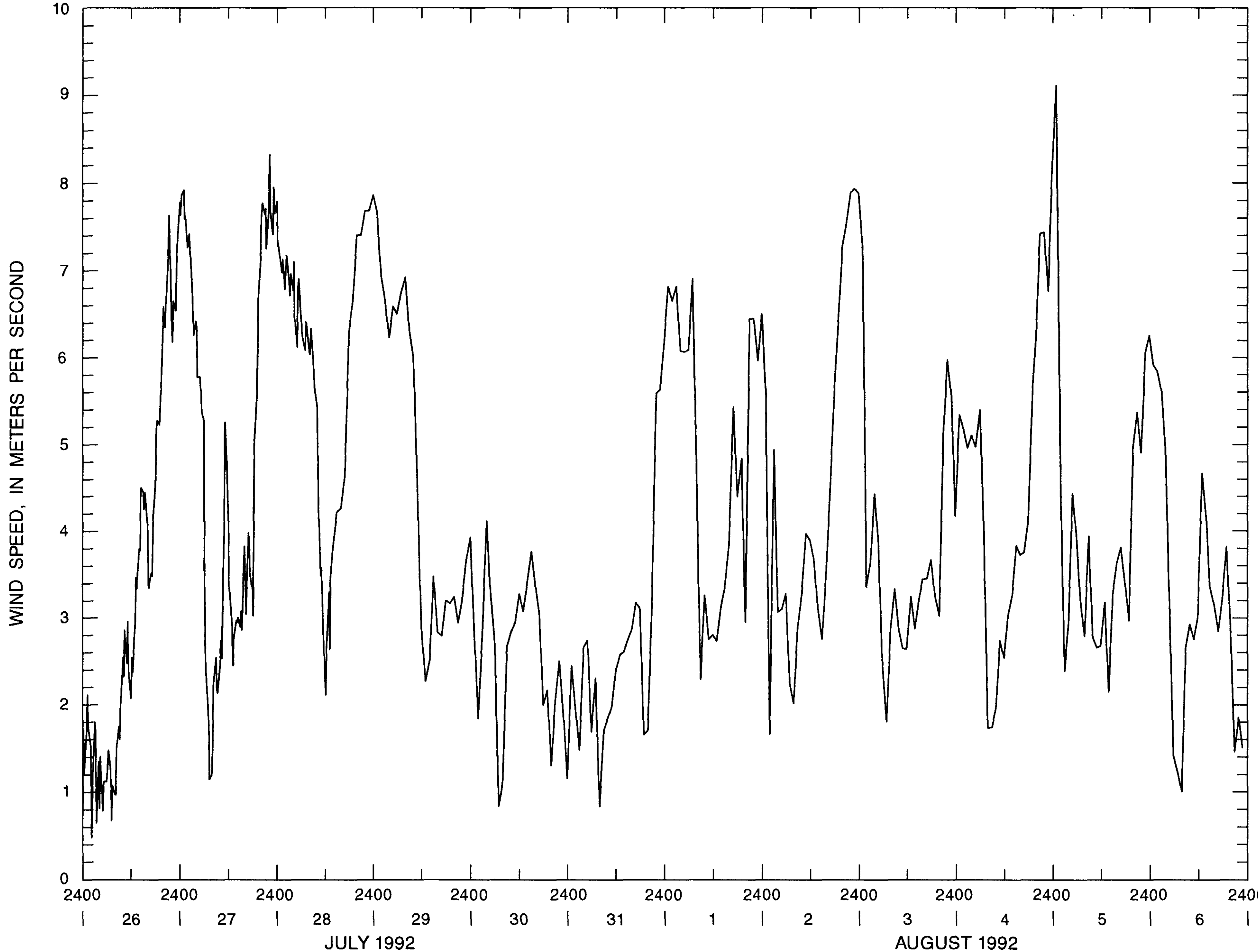

Figure 20.--Wind speed at 3 meters above the canopy for the Black Rock Valley site, July 26 to August 6, 1992.

Water Budgets

Long-term ET estimates are important to water-resource 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. Precipitation (PR), ET, surface runoff (RO) from other areas, and recharge (RCH) to subsurface systems make up the water budget at the eastern Washington sites:

$$PR + RO = ET + RCH$$

When estimates of precipitation, surface runoff, and ET are known, the remainder of the water budget is the change in subsurface systems.

Annual water budgets were calculated for the grass and sage lysimeter sites and the Snively Basin site. A water budget for the Turnbull meadow site was not possible because estimates of precipitation, ET, and soil moisture that occurred in the year before the study began could not be accurately made (S. Tomlinson, U.S. Geological Survey, written commun., 1994). Water budgets could not be developed for the Turnbull marsh site and the Black Rock Valley site because of limited data and unknown antecedent conditions. For the Snively Basin, grass lysimeter, and sage lysimeter sites, water budgets were formulated for 1991 and 1992 with collected data. Water budgets were also formulated for the Snively Basin site with ET estimates from the deep-percolation model. The water budgets for 1991 for the Snively Basin, grass and sage lysimeter sites showed that 100 percent of the precipitation became ET; for 1992, about 91 to 99 percent of the precipitation became ET.

Grass and Sage Lysimeter Sites

Water budgets for the grass and sage lysimeter sites were determined for two periods: August 20, 1990 to September 30, 1991 (1991 water budget) and October 1, 1991 to September 30, 1992 (1992 water budget). At the beginning and end of these periods, ET and surface soil moisture were near zero (table 2). In each case, daily ET was about 0.1 to 0.2 mm, and surface (upper 0.15 m) soil moisture measured about 2.5 percent. On the basis of lysimeter data, cumulative ET and precipitation for the grass and sage lysimeter sites were nearly identical (fig. 21). Also, the overall ratios of ET-to-precipitation for the lysimeter sites for 1991 and 1992 agreed within 8 percent of the ratios determined for the Snively Basin site.

The water budgets for the grass and sage lysimeter sites were determined in two ways. In the first method, ET and precipitation were calculated for each lysimeter site for each day (values from the two lysimeters at each site were averaged), and the totals of each were accumulated for the water-budget periods. In the second method, the actual lysimeter weights at the beginning and end of the water budget periods were compared (with values from the two lysimeters at each site averaged). The second method allowed an annual budget not affected by all of the lysimeter weight changes not caused by precipitation or ET, such as blowing and drifting snow or animal trespass. In each case, the two methods agreed within 4 percent of each other for both lysimeter sites. The water budgets presented assume that runoff equals zero for the periods of study at the lysimeter sites and that water is able to drain freely from the bottoms of the lysimeters.

On the basis of daily ET and precipitation values for 1991 at the grass lysimeter site, lysimeter ET and precipitation totalled 215 mm and 212 mm, respectively. This gave a 101 percent ET-to-precipitation ratio, indicating that all precipitation was returned to the atmosphere as ET and that there was no subsurface-system recharge. For the 1991 water budget, the ratio of the ending lysimeter weight (September 30, 1991) to the beginning weight (August 20, 1990) was 100 percent, indicating no net change in moisture storage in the soil monolith. This showed that precipitation and ET were equal, and no recharge occurred during the period.

For 1992 at the grass lysimeter site, the weighing lysimeters measured daily totals of 251 mm of ET and 266 mm of precipitation. This gave a 94.4 percent ET-to-precipitation ratio, indicating about 15 mm, or 5.6 percent of the precipitation, might have become subsurface-system recharge (which includes stored soil moisture). From the actual lysimeter weights, the ratio of the ending weight (September 30, 1992) to the beginning weight (October 1, 1991) was 98.0 percent. This indicated that 3.6 percent less water became subsurface-system recharge than that showed by the water budget which used daily ET and precipitation totals.

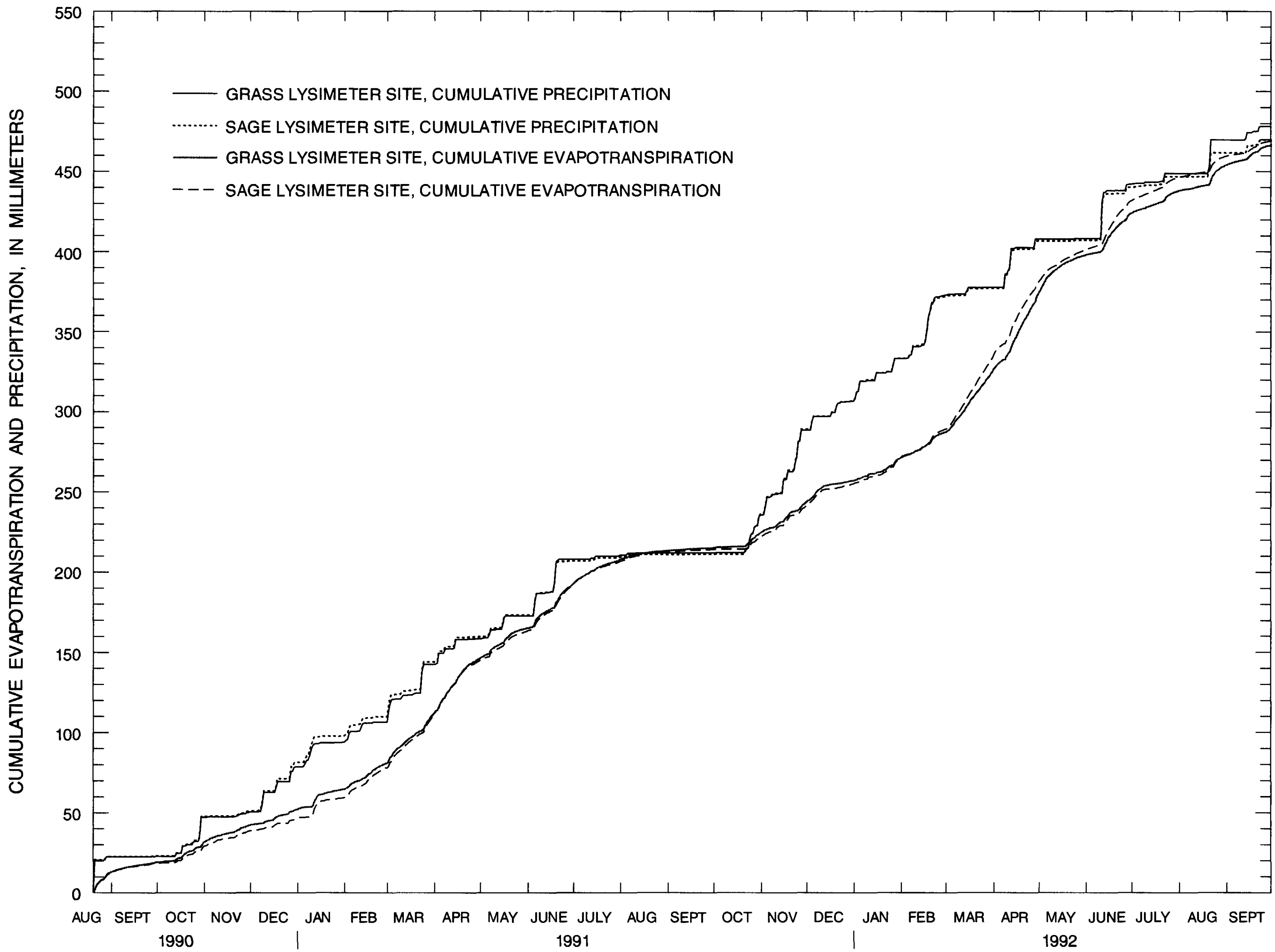

Figure 21.--Cumulative precipitation and evapotranspiration from weighing lysimeters at the grass and sage lysimeter sites, August 20, 1990 to September 30, 1992. Evapotranspiration and precipitation estimates are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

Daily totals of ET and precipitation for 1991 at the sage lysimeter site were almost identical to those at the grass lysimeter site. The weighing lysimeters at the sage lysimeter site measured 214 mm of ET and 211 mm of precipitation. This gave a 101 percent ET-to-precipitation ratio, indicating that all precipitation had been returned to the atmosphere as ET, with no subsurface-system recharge. From the actual sage lysimeter weights for the 1991 water budget, the ratio of the ending weight (September 30, 1991) to the beginning weight (August 20, 1990) was 100 percent, indicating no net change in moisture storage in the soil monolith. ET and precipitation were equal during this period.

For 1992 at the sage lysimeter site, the weighing lysimeters measured daily totals of 255 mm of ET and 259 mm of precipitation. This gave a 98.5 percent ET-to-precipitation ratio, which indicated that about 4 mm, or 1.5 percent of the precipitation, might have become subsurface-system recharge. From the actual sage lysimeter weights for the 1992 water budget, the ratio of the ending weight (September 30, 1992) to the beginning weight (October 1, 1991) was 99.3 percent. This ratio indicated almost no recharge to subsurface systems.

On the basis of the lysimeter data for 1992, about 2.7 percent more subsurface-system recharge was estimated for the grass lysimeter site than for the sage lysimeter site. This might indicate that subsurface-system recharge would be greater in grass-covered areas than in sagebrush-covered areas, a condition supported by some studies (Link and others, 1990). However, the water budget estimates might also indicate that the sage plants in the lysimeters at the sage lysimeter site were root-bound by the lysimeters. If the sage plants were root-bound, they would tend to use all available water in the lysimeters (just like a root-bound potted plant) and would appear stressed during dry periods because the roots could not spread further to obtain more-deeply stored water. A root-bound condition may be indicated by the observation that plants in the lysimeters had fewer live branches and sparser blooms than plants outside the lysimeters. However, for the grass and sage lysimeter sites, water budget results were fairly close. The 2.7 percent difference in recharge could also simply be instrument or measurement error. More years of data-collection and comparison at the grass and sage lysimeter sites would be needed to more definitely assess the root-bound effect.

Snively Basin Site

Seasonal patterns of precipitation and ET at the Snively Basin site were similar to those of the grass lysimeter site (fig. 22). The greatest precipitation was received in winter and early spring and most of the annual ET occurred in spring. Also, the least precipitation and ET for the year usually occurred in late summer or early fall. Because the Snively Basin site is only 5 km from the grass lysimeter site, this similarity was expected. However, amounts of precipitation and ET were different. The Snively Basin site averaged 13 percent more precipitation and 9 percent more ET than the grass lysimeter site from August 20, 1990 to September 30, 1992.

For the Snively Basin site, water budgets were calculated for August 20, 1990, to September 30, 1991, and for October 1, 1991, to September 30, 1992. These budgets used ET estimates from collected data and from results of the deep-percolation model. August 20, 1990, was chosen as a starting point for the water budget because antecedent conditions were such that change in surface soil-moisture storage and ET were near zero. The last precipitation over 2 mm prior to August 20, 1990 occurred on June 6, surface soil moisture averaged only 2.4 percent, and grasses were completely dormant. Similar conditions existed on September 30, 1991, and September 30, 1992, so water budgets were analyzed separately for August 20, 1990, to September 30, 1991 (1991 budget), and October 1, 1991, to September 30, 1992 (1992 budget).

A tipping-bucket rain gage measured precipitation at the Snively Basin site for the entire period of study. The gage worked well except during sub-freezing weather, when the tipping mechanism stuck because of ice on the mechanism or snow did not penetrate the screen of the collection funnel. When temperatures rose above freezing, however, the snow melted and was recorded. During the winter of 1990-91, the tipping-bucket gage measured only about half the precipitation that fell as snow; this was shown by a comparison of the Snively Basin tipping-bucket precipitation data with precipitation data collected by a storage gage about 30 m away. Precipitation data for the winter was supplemented by data from this storage gage to provide more accurate precipitation amounts and timing. The winter of 1991-92 was unusually mild with little snow, so no adjustments for snowfall were made to the collected data. During high winds, however, the gage may not have measured precipitation accurately because it was not shielded (Linsley and others, 1982).

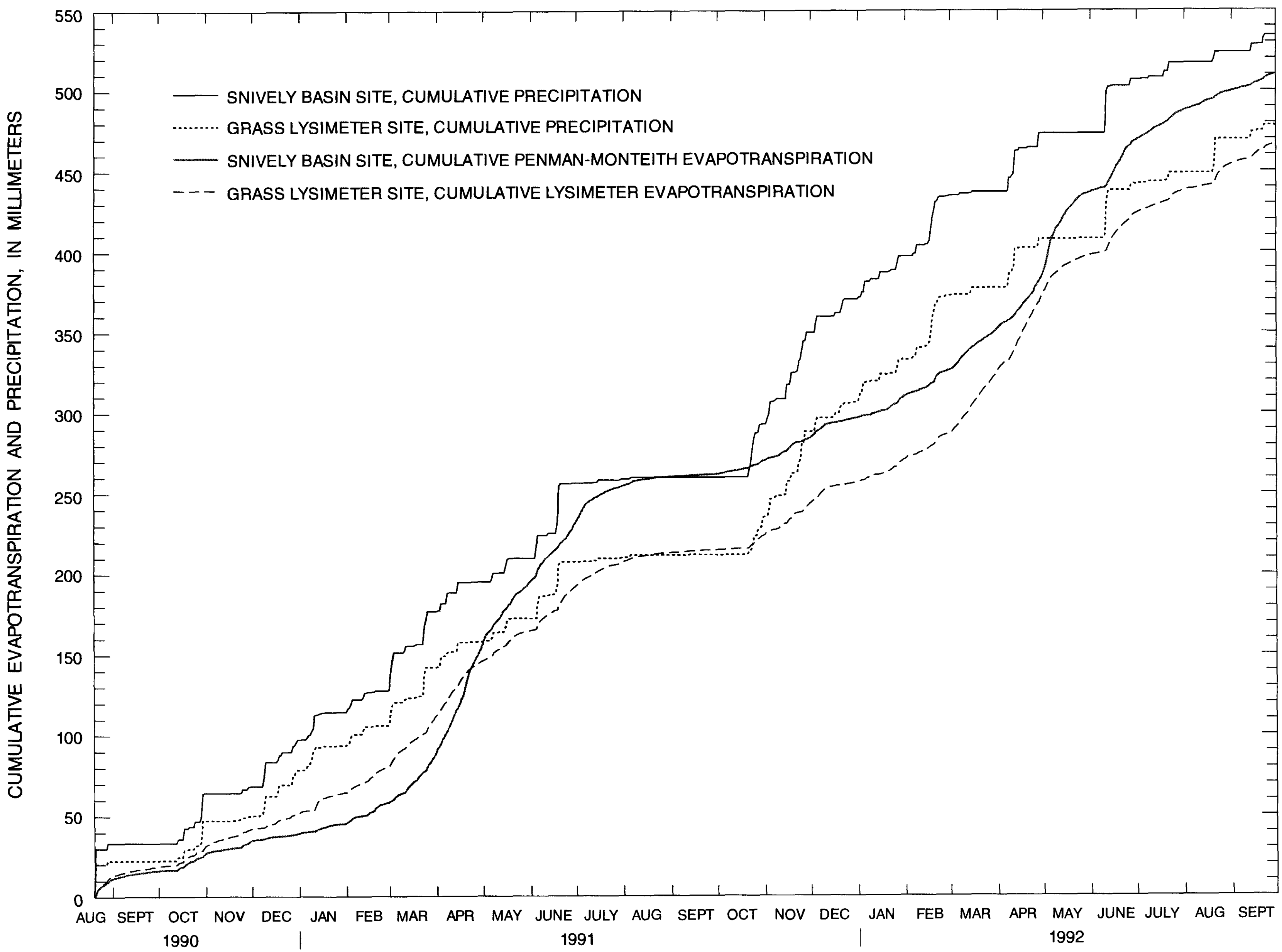

Figure 22.--Cumulative precipitation and evapotranspiration at the Snively Basin and grass lysimeter sites, August 20, 1990 to September 30, 1992. Evapotranspiration and precipitation estimates for the grass lysimeter site are based on data collected and provided by Battelle, Pacific Northwest Laboratories.

Although dewfall and trace precipitation were not measured at the Snively Basin site, dewfall is estimated at less than 5 percent of the precipitation on the ALE Reserve (Rickard and others, 1988). To account for unmeasured trace precipitation, dewfall, and wind effects on the tipping-bucket gage, the measured precipitation was increased by 5 percent, on the basis of Rickard and other's (1988) estimate. The 5 percent increase in precipitation at the Snively Basin site was distributed evenly over all the precipitation events during the period of study. The measured precipitation was multiplied by 1.05 to estimate the precipitation used in the Snively Basin water budget. Five percent was considered a conservative estimate of the unmeasured precipitation; possibly it was higher, as was shown at other sites. Tipping-bucket precipitation was 9.5 percent less than weighing-lysimeter measured precipitation at the grass lysimeter site in April and May 1991 (Tomlinson, 1995). Also, tipping-bucket precipitation averaged 12 percent less than precipitation measured by a storage gage near the Turnbull meadow site in 1991 and 1992 (S. Tomlinson, U.S. Geological Survey, written commun., 1994).

Surface runoff was assumed to be zero for the period of study. Only three storms exceeded 20 mm of precipitation (August 21, 1990, June 20, 1991, and June 12, 1992, table 4), and the overland runoff at the Snively Basin site was assumed to be very low because the soils were very dry and likely to readily absorb any rainfall.

At the beginning of the water budget period (August 20, 1990), soil moisture in the top 0.15 m of the profile at the Snively Basin site was measured at 2.4 percent, and ET for the day was estimated at 0.1 mm. One day later, 28.19 mm of rainfall was measured there. A steep slope occurred in the cumulative ET plot (fig. 23) after the August 21 rainfall, indicating high daily ET. This steep slope was followed by a leveling-off period in late September and early October 1990, when ET was near zero. These leveling-off periods occurred during late summer or early fall for each year that data were collected at the Snively Basin site and coincided with near-zero ET and surface soil moisture under 3 percent. In 1991, this near-zero leveling-off period occurred from August until late October (table 4, fig. 23). In 1992, the near-zero leveling-off period occurred from late August to mid-September (table 4), although it was not as marked as it was in 1991.

Precipitation from October to February each year added moisture to the soil profile, while ET remained fairly low because of low net radiation, low temperatures, and an inactive plant canopy. For the 1991 water budget, only 16 percent of the ET occurred from October to February, while in the 1992 water budget, 26 percent of the ET occurred from October to February. The larger percentage in the 1992 water budget reflects the higher ET loss during the warmer winter of 1991-92, compared with the previous winter.

From March to July each year, plants quickly used up the water stored in the soil profile, and the slope of the cumulative ET plot steepened dramatically (fig. 23). In the 1991 water budget, 76 percent of the ET occurred from March to July; April alone accounted for 25 percent. In the 1992 water budget, 65 percent of the ET occurred from March to July, with May accounting for 21 percent of the annual total ET.

From August to September, the cumulative ET plot leveled out again as rainfall occurred only infrequently and soil moisture approached 2.5 percent. The slope of the plot became steeper during August and September only for short periods following major rainfalls, such as that on August 21, 1990.

The annual total of ET calculated with the Penman-Monteith method agreed well with annual totals of ET from the model—within 0.4 percent in 1991 and 1.2 percent in 1992, although daily, monthly, and seasonal values varied. The 1991 water budgets included 260 mm of precipitation and totalled 262 mm of Penman-Monteith ET and 261 mm of model ET. This gave a 101 percent ET-to-precipitation ratio with the Penman-Monteith method and 100 percent ET-to-precipitation ratio with the model. Results from both methods indicated that all precipitation from August 20, 1990, to September 30, 1991, was returned to the atmosphere as ET— that is, no water was available for recharge to subsurface systems. The 1992 water budgets included 274 mm of precipitation and totalled 248 mm of Penman-Monteith ET and 251 mm of model ET. This gave a 90.5 percent Penman-Monteith ET-to-precipitation ratio and a 91.6 percent model ET-to-precipitation ratio. Recharge to subsurface systems for the 1992 budget was estimated at 26 mm from the Penman-Monteith estimates and 23 mm from the model ET estimates. The deep-percolation model results indicated that this recharge occurred during February 1992.

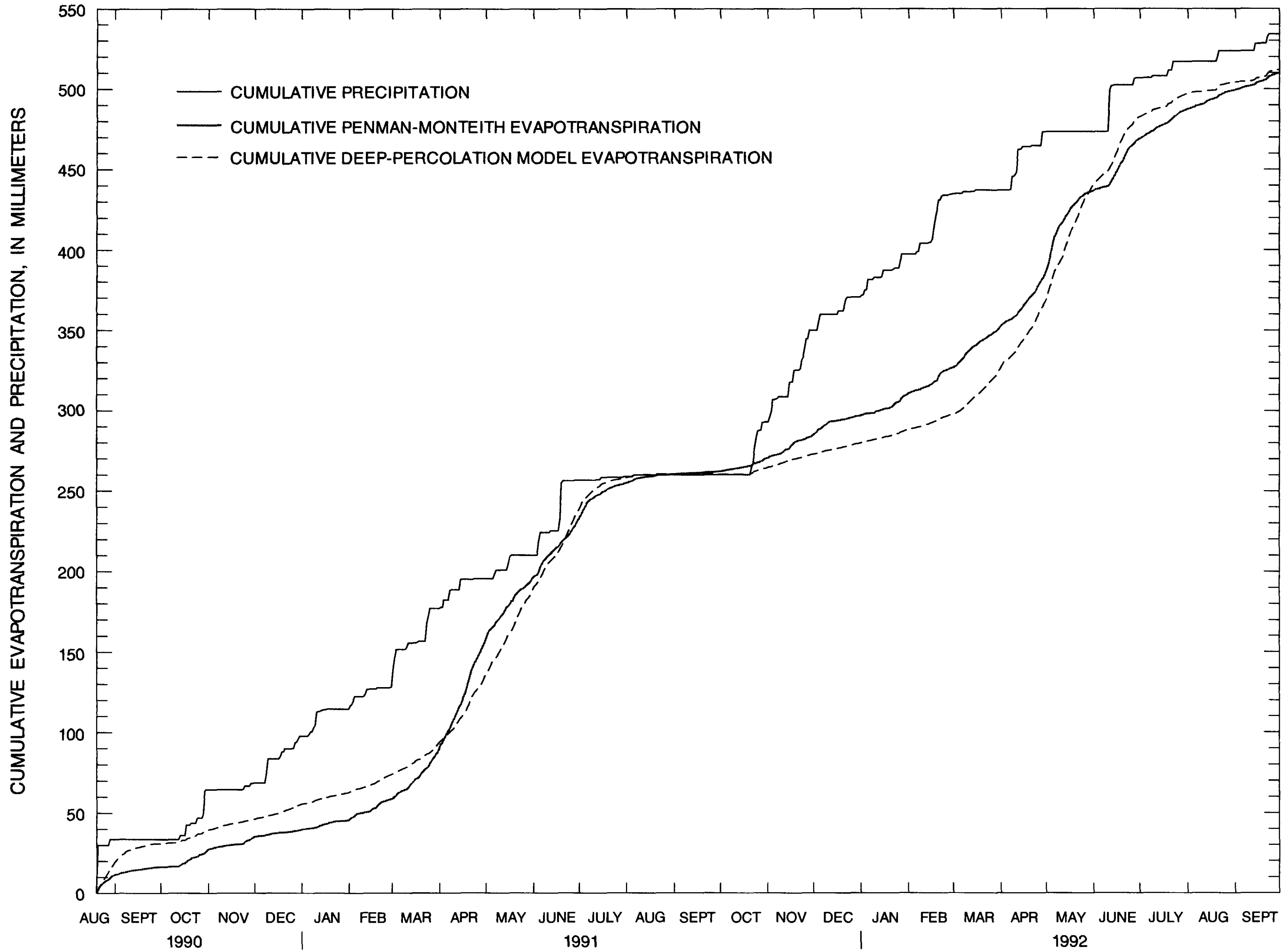

Figure 23.--Cumulative precipitation and evapotranspiration from the Penman-Monteith method and deep-percolation model at the Snively Basin site, August 20, 1990 to September 30, 1992.

The closeness of the 1992 recharge estimates calculated by the Penman-Monteith method and model could be coincidence, however. There are uncertainties in instrumentation precision, precipitation catch, the winter Penman-Monteith ET estimates, and the often large daily disagreement between deep-percolation model and Penman-Monteith ET estimates. Given these uncertainties, actual recharge at the Snively Basin site for 1992 could have been somewhat larger or smaller than recharge estimated by the two methods. Perhaps 1992 recharge at the Snively Basin site was as low as estimates from lysimeter data at the nearby grass and sage lysimeter sites (4 to 15 mm).

Although there are some uncertainties in all the methods used—the weighing lysimeters at the grass and sage lysimeter sites, the Penman-Monteith method (which incorporated Bowen-ratio measurements) and the deep-percolation model for the Snively Basin site—all estimated nearly the same magnitude of recharge results. Results from all the methods indicated that recharge at the Snively Basin site was very low: probably zero in 1991, and less than 10 percent of the annual precipitation in 1992.

SUMMARY AND CONCLUSIONS

Evapotranspiration (ET) was evaluated at six sites in Benton, Spokane, and Yakima Counties, Washington. Three sites were located on the Arid Lands Ecology Reserve in Benton County: one at a dense-canopy grassland in Snively Basin (Snively Basin site), one at sparse-canopy grassland adjacent to a pair of weighing lysimeters (grass lysimeter site), and one at a sagebrush grassland adjacent to two weighing lysimeters (sage lysimeter site). Two sites were located on the Turnbull National Wildlife Refuge in Spokane County: one at a full-canopy grassland in a meadow (Turnbull meadow site); the other at a full-canopy grassland near a marsh (Turnbull marsh site). The sixth site was located in a sagebrush grassland in the Black Rock Valley in Yakima County (Black Rock Valley site).

The periods of study used at the six sites varied, ranging from 5 months at the Black Rock Valley site to more than 2 years at the Snively Basin, grass lysimeter, and sage lysimeter sites. The periods of study were May 1990 to September 1992 for the Snively Basin, grass lysimeter, and sage lysimeter sites, May 1991 to September 1992 for the Turnbull meadow site, May 1991 to April 1992 for the Turnbull marsh site, and March to September 1992 for the Black Rock Valley site.

The Bowen-ratio method, Penman-Monteith method, weighing lysimeters, and a deep-percolation model were used to estimate ET at the study sites. Evapotranspiration and energy-budget fluxes were calculated with the Bowen-ratio and Penman-Monteith methods for the Snively Basin site, the Turnbull meadow site, and the Black Rock Valley site. Daily ET for the Snively Basin site was also estimated with a deep-percolation model for the Columbia Plateau. The Bowen-ratio method and weighing lysimeters were used at the grass and sage lysimeter sites. The Penman-Monteith method was used at the Turnbull marsh site.

Daily ET at the sites ranged from less than 0.2 millimeter during very dry or cold periods to more than 4 millimeters after heavy rainfall or during periods of peak transpiration. At all sites, peak ET occurred in spring, coinciding with plant growth, and the lowest ET occurred in late summer and winter, coinciding with plant dormancy and extremely hot or cold temperatures. About two-thirds of the ET for the year occurred from March to July while only about one-fifth occurred from October to February at the Snively Basin site.

Daily ET estimated with the Bowen-ratio method and the Penman-Monteith method agreed very well at the Snively Basin, Turnbull meadow, and Black Rock Valley sites. The close correlation was expected, however, because the Bowen-ratio method was used to calibrate the Penman-Monteith method for the canopy resistance. Squares of the correlation coefficients (r^2) were 0.95 at the Snively Basin site, 0.96 at the Turnbull meadow site, and 0.91 at the Black Rock Valley site. The r^2 for the Black Rock Valley site was lower than the other two sites primarily because windier conditions at night produced higher estimates of ET at night than those estimated with the Bowen-ratio method.

ET at the grass and sage lysimeter sites agreed well with each other on a daily and annual basis. The r^2 on the daily values was 0.93. Totals of ET for the period August 20, 1990 to September 30, 1992 for both sites were very close, with 466 mm estimated at the grass site, and 469 millimeters estimated at the sage site.

Ratios of ET-to-precipitation at the Snively Basin site—(100 percent in 1991 (August 20, 1990 to September 30, 1991) and 91 percent in 1992 (October 1, 1991 to September 30, 1992)—agreed well with the same ratios at the grass and sage lysimeter sites (100 percent in 1991; 94 to 99 percent in 1992). However, there were some differences in daily and seasonal ET estimates. During winter, high ET spikes were shown by weighing lysimeters during high winds, while less ET was shown by the Penman-Monteith method at the Snively Basin site. During late spring, ET was usually much lower at the grass and sage lysimeter sites than at the Snively Basin site. This was due to 13 percent higher precipitation at the Snively Basin site than at the lysimeter sites. The wetter environment at the Snively Basin site allowed grasses to continue growing well into June, while at the lysimeter sites, the grasses were senescing in late April and May and usually dormant or perished by June.

For the Snively Basin site, deep-percolation model ET estimates did not agree well with Penman-Monteith ET estimates on a daily or seasonal basis; however, they did agree well on an annual basis. The r^2 for the daily values was 0.57, indicating much variability. Model ET differed from Penman-Monteith ET during several periods. After heavy summer rainfalls, model ET was usually higher than Penman-Monteith ET. During the winter, model ET was usually less than Penman-Monteith ET. During early to mid-spring, the model showed much lower ET than the Penman-Monteith method did; later in the spring, the model showed much higher ET than the Penman-Monteith method. During windy periods, model ET was less than Penman-Monteith ET. The differences averaged out on an annual basis, however, as annual ET totals estimated by the two methods agreed within about 1 percent of each other for 1991 and 1992. The differences between Penman-Monteith ET and model ET were probably due to (1) differences between the plant growth curve used by the model and the actual growth of grasses at the Snively Basin site; (2) the model not incorporating wind speed, which is an important function in the Penman-Monteith method; and (3) errors in the collected data or variable inputs to the model, particularly for small ET values.

Water budgets for the Snively Basin, grass lysimeter, and sage lysimeter sites were formulated from estimates of precipitation, ET, and surface runoff. Surface runoff was assumed to be zero for all sites because the most intense rainfalls occurred during periods when the soil was very dry and probably could absorb most of the rainfall. Trace precipitation, dewfall, and precipitation not measured by the tipping-bucket rain gage, because of wind effects, were estimated at 5 percent of the measured precipitation for the Snively Basin site. For the water budget at the Snively Basin site, 5 percent was added to the measured precipitation to provide more accurate estimates. No adjustments were made for precipitation measured by weighing lysimeters at the grass and sage lysimeter sites.

For the Snively Basin site, annual totals of Penman-Monteith ET estimates agreed with annual totals of model ET by 0.4 percent in 1991 and 1.2 percent in 1992. For the 1991 budget, Penman-Monteith ET totalled 101 percent and model ET totalled 100 percent of the 260 millimeters of precipitation. In the 1992 budget, Penman-Monteith ET totalled 90.5 percent and model ET totalled 91.6 percent of the 274 millimeters of precipitation. Recharge for the 1991 budget was zero; for 1992, it ranged from 23 millimeters with model ET estimates, to 26 millimeters with Penman-Monteith ET estimates. The model indicated the 1992 recharge occurred in February. The close agreement of the recharge to subsurface systems estimated by the Penman-Monteith method and the model was probably coincidence, given the variability of the daily and seasonal ET estimates.

Water budgets based on weighing lysimeter data at the grass and sage lysimeter sites agreed within 1 percent of each other for 1991 and within 5 percent of each other for 1992. For 1991, all of the measured precipitation (212 millimeters at the grass lysimeter site and 211 millimeters at the sage lysimeter site) became ET. For 1992, 94 to 98 percent of the 266 millimeters of precipitation became ET at the grass lysimeter site, while 98 to 99 percent of the 259 millimeters of precipitation became ET at the sage lysimeter site.

No water budgets were formulated for the Turnbull meadow and marsh sites or Black Rock Valley site because of the inability to determine antecedent precipitation, ET, and soil moisture, in addition to the short periods of study.

In conclusion, this report makes the following findings:

1) The Bowen-ratio method can be used to calibrate the Penman-Monteith method for the canopy resistance as an alternate method of calculating ET at grass and sage sites in eastern Washington. However, the canopy resistances determined in this way may include error from a number of sources, such as instrument error, and should be viewed as a calibration factor between the two methods. Furthermore, this canopy resistance varies tremendously depending on site conditions. Thus, actual ET estimated by an independent method such as weighing lysimeters or the Bowen-ratio method will be needed to calibrate the Penman-Monteith method on a daily basis. The Penman-Monteith method cannot be used to make accurate daily estimates of ET without calibration for the canopy

resistance during spring, summer, and fall. Reasonable estimates might be made with the Penman-Monteith method during the winter because the canopy resistance can often be estimated because of frequent rain, snow, or fog. At other times during winter, errors in estimating canopy resistance may average out and should not be of great concern because winter ET is very low and only a small percentage of the annual ET.

2) The Penman-Monteith method appears to estimate higher ET during windy periods than does the Bowen-ratio method. Thus, the Penman-Monteith method may be more sensitive to higher wind speeds than the Bowen-ratio method. Weighing-lysimeter data show that high ET can occur during periods of high wind, even at night, when net radiation provides no source of energy.

3) For the grass lysimeter, sage lysimeter, and Snively Basin sites on the Arid Lands Ecology Reserve, the ratio of ET to precipitation on an annual basis was nearly the same at each site for 1991 and 1992 even though the amounts of precipitation and ET were different. In each case, 90 to 100 percent of the precipitation became ET. Greater precipitation at the Snively Basin site, compared with the lysimeter sites, appeared to result in higher ET, but not necessarily increased recharge to subsurface systems (soil moisture, the unsaturated zone, and ground water).

4) For the Snively Basin site, the Columbia Plateau deep-percolation model estimated almost the same ET as the Penman-Monteith method on an annual basis but not on a daily, monthly, or seasonal basis. Observed differences may have been partly due to the model not incorporating wind speed in estimating ET and to the model using unrepresentative growth curves for grasses in predicting transpiration. The model and the Penman-Monteith method estimated almost the same amounts of annual recharge to subsurface systems in 1991 and 1992, but this could have been coincidence. Further comparisons of this model need to be made at sites in the Columbia Basin to better assess whether or not the model could be used to estimate daily, monthly, or seasonal ET and recharge.

5) Although precipitation is difficult to accurately measure, ET and precipitation are the most important components of the water budget in eastern Washington. Because of wind effects on tipping-bucket gages as well as no measurements of trace precipitation or dew, measured precipitation at the eastern Washington sites was almost certainly underestimated by the tipping-bucket gages. Estimates of the under-measurement range from 5 to 12 percent at these sites. Weighing lysimeters probably can accurately measure precipitation in most cases except during periods when precipitation and ET occur during the same measurement interval and cancel each other out. This error is probably small most of the time, because ET is usually near zero during precipitation, but it could be very large in some cases, such as when high precipitation at the beginning of a measurement interval was followed by high ET during the rest of the measurement interval.

6) ET is difficult to accurately estimate with the Bowen-ratio method in semiarid areas such as eastern Washington. The Bowen-ratio instruments used in this study were prone to failure when used over long periods of time because of inexplicable calibration drift on cooled mirrors, possible leaks in the cooled-mirror chamber, icing of the mirror caused by dew points below freezing (not uncommon in eastern Washington), failure of electronic and mechanical components such as the pump motor for the cooled mirror, and damage to sensors caused by animals and hail. Additionally, vapor-pressure gradients may be too small to accurately measure with available instruments. Unfortunately, many of the vapor-pressure measurement errors were not readily apparent from the collected data. Precision of all instruments is also a factor in determining ET and may cause ET estimates to vary by plus or minus 12 percent.

7) Caution should be used when determining water budgets and making ET estimates in semiarid, and perhaps other, areas. Two or more completely independent methods may be required at a site to accurately assess ET and determine a water budget. In the study at the Snively Basin site, the measurements by the weighing lysimeters at the nearby weighing-lysimeter sites helped provide more confidence in the Bowen-ratio and Penman-Monteith measurements that were made. Only when results from two or more methods agree can one be reasonably sure that the instruments are making accurate, representative measurements.

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