

RAINFALL, EVAPOTRANSPIRATION, TOTAL SOIL-
WATER POTENTIAL, AND SOIL-WATER CONTENT
AT A SAGEBRUSH SITE AND A REPLACEMENT-
VEGETATION SITE NEAR FORT
DEFIANCE, ARIZONA, 1989-91

By Carole L. Thomas

U.S. GEOLOGICAL SURVEY

Open-File Report 94-43

Prepared in cooperation with the
NAVAJO NATION FORESTRY DEPARTMENT



Albuquerque, New Mexico

1994

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Robert M. Hirsch, *Acting Director*

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
4501 Indian School Rd. NE, Suite 200
Albuquerque, New Mexico 87110

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CONTENTS

	Page
Abstract	1
Introduction	1
Purpose and scope	2
Description of the study area	2
Acknowledgment.....	2
Data-collection methods and data summary.....	5
Rainfall.....	8
Evapotranspiration	8
Total soil-water potential	16
Soil-water content	19
Replacement of vegetation at site 1	22
Factors affecting growth of replacement vegetation	25
Summary	28
References cited.....	29

FIGURES

1. Map showing location of the study area.....	3
2. Photograph showing vegetation at site 1 near Fort Defiance, Arizona.....	4
3. Photograph showing vegetation at site 2 near Fort Defiance, Arizona.....	4
4. Diagram showing instrumentation used for the rainfall, micrometeorological, and soil-matric-potential data-collection sites	6
5-7. Graphs showing daily rainfall and daily evapotranspiration at:	
5. Site 1, May 25-November 8, 1989	9
6. Site 2, May 25-November 8, 1989	10
7. Site 1, April 18-November 28, 1990.....	11

FIGURES--Concluded

	Page
8-12. Graphs showing:	
8. Daily rainfall and daily evapotranspiration at site 2, April 18-November 28, 1990.....	12
9. Daily rainfall and daily evapotranspiration at site 1, April 17-November 6, 1991.....	13
10. Daily rainfall and daily evapotranspiration at site 2, April 17-November 6, 1991.....	14
11. Daily total soil-water potential at site 1, May 25, 1989, through November 6, 1991	17
12. Daily total soil-water potential at site 2, May 25, 1989, through November 6, 1991	18
13. Photograph showing cleared land at site 1 (right) compared to adjacent sagebrush (left).....	23
14. Photographs showing establishment of grasses and shrubs at site 1	24
15. Graph showing energy balance and daily rainfall at site 2 near Fort Defiance, Arizona, August 30-September 2, 1990.....	26

TABLE

1. Volumetric soil-water content measured at sites 1 and 2, November 1990, April 1991, and November 1991	20
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CONVERSION FACTORS AND VERTICAL DATUM

In this report, most measurements are given first in inch-pound units followed by the metric unit; if the data were collected as a metric unit, the metric unit is given first followed by the inch-pound unit.

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

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ABSTRACT

The Navajo Nation Forestry Department established a growth of four species of native grasses and two species of native shrubs on formerly sagebrush-covered land about 6 miles north of Fort Defiance, Arizona. The native grasses and shrubs grew under conditions of natural precipitation and soil fertility. This provided alternate grazing areas for tribal livestock. Tribal livestock previously had been grazed on timber-producing land, killing seedlings planted for reforestation.

The U.S. Geological Survey monitored rainfall, evapotranspiration, total soil-water potential, and soil-water content at a sagebrush site and a site planted with grasses and shrubs north of Fort Defiance, Arizona, to document hydrologic conditions during the experiment. Daily rainfall during the April through November 1989-91 data-collection period ranged from 0 to 1.21 inches (0 to 30.7 millimeters). Evapotranspiration during the data-collection period generally ranged from about 0.5 to 2 millimeters per day (0.02 to 0.08 inch per day), increasing to 2 to 5 millimeters per day (0.08 to 0.20 inch per day) after rainfall. The total soil-water potential generally ranged from about -4 to 0 bar (-58 to 0 pound per square inch). Volumetric soil-water content ranged from 5.7 to 65.9 percent. Soils were wetter during the April data-collection period than during the November data-collection periods.

INTRODUCTION

The Navajo Nation Forestry Department uses areas of the reservation for timber production that require reforestation after logging is completed. Tribal members use these same areas for summer grazing of sheep and goats, which kill the tree seedlings planted for reforestation. Areas are needed that will support vegetative growth for grazing. Replanting sagebrush-covered areas with suitable vegetation for livestock could alleviate the problem, if the available water would support a good stand of replacement vegetation. The Navajo Nation Forestry Department and the U.S. Geological Survey entered into a cooperative study in April 1988 to assess the potential of sagebrush-covered areas to support replacement grasses and shrubs. The U.S. Geological Survey collected data to document the hydrologic conditions at sagebrush and replacement-vegetation areas. Understanding the hydrologic conditions would guide managers in assessing the potential for sagebrush-covered areas to be replaced with grasses and shrubs.

Purpose and Scope

The purpose of this report is to present, describe, and summarize seasonal data on rainfall, evapotranspiration, and total soil-water potential, and measurements of soil-water content at a sagebrush-covered site and a replacement-vegetation site. The two sites were 26 acres (105,222 square meters) in size. The seasonal data were collected during the growing seasons, generally May through November, for 1989-1991. Measurements of soil-water content were made in November 1990, April 1991, and November 1991.

Description of the Study Area

The Navajo Nation Forestry Department selected two sagebrush-covered test sites of 26 acres (105,222 square meters) each. These sites are located within the Navajo Indian Reservation about 1.5 miles (2.4 kilometers) apart; site 1 is about 5.3 miles (8.6 kilometers) and site 2 is about 6.8 miles (10.9 kilometers) north of Fort Defiance, Arizona (fig. 1). The altitude of the land surface at site 1 is about 7,500 feet (2,290 meters) and at site 2 is about 7,480 feet (2,280 meters) above sea level. Vegetation at site 1 (fig. 2) and site 2 (fig. 3) is predominantly sagebrush. Scattered grasses and weeds are present, as well as scattered juniper and piñon. Site 1 lies within a slight topographic depression and site 2 lies atop a slight hill. The aspect at both sites is easterly. No surface-drainage channels dissect either site.

The soils at sites 1 and 2 are 10 to 20 inches (250 to 500 millimeters) thick, moderately permeable, and have medium texture (Morrison-Maierle, Inc., 1981, p. 6-4 to 6-6). Erosion is moderate and the land surface slopes between 1 and 8 percent (Morrison-Maierle, Inc., 1981, p. 6-4 to 6-6). U. S. Geological Survey personnel described soil samples at the two sites as light-brown to reddish-brown, silt to fine-grained sand, with occasional white, angular, cemented grains. A grayish-pink to moderate-reddish-brown sandstone lies beneath the shallow soil.

Precipitation within the study area occurs as snow in the winter and usually as rain during the rest of the year. Thunderstorms are common during July and August. Average annual precipitation at Window Rock, Arizona, the climatological-data station closest to the study sites (fig. 1), is 11.51 inches per year (292.4 millimeters per year) (U.S. Department of Commerce, 1990, p. 4-5). During 1990 the temperature at Window Rock ranged from a low of minus 23 degrees Fahrenheit (minus 31 degrees Celsius) to a high of 99 degrees Fahrenheit (37 degrees Celsius) (U.S. Department of Commerce, 1990, p. 13).

Acknowledgment

Navajo Nation officials and residents have graciously allowed access to their property for installation of scientific measurement equipment and for monitoring and maintenance of this equipment. Their help and cooperation are gratefully acknowledged.

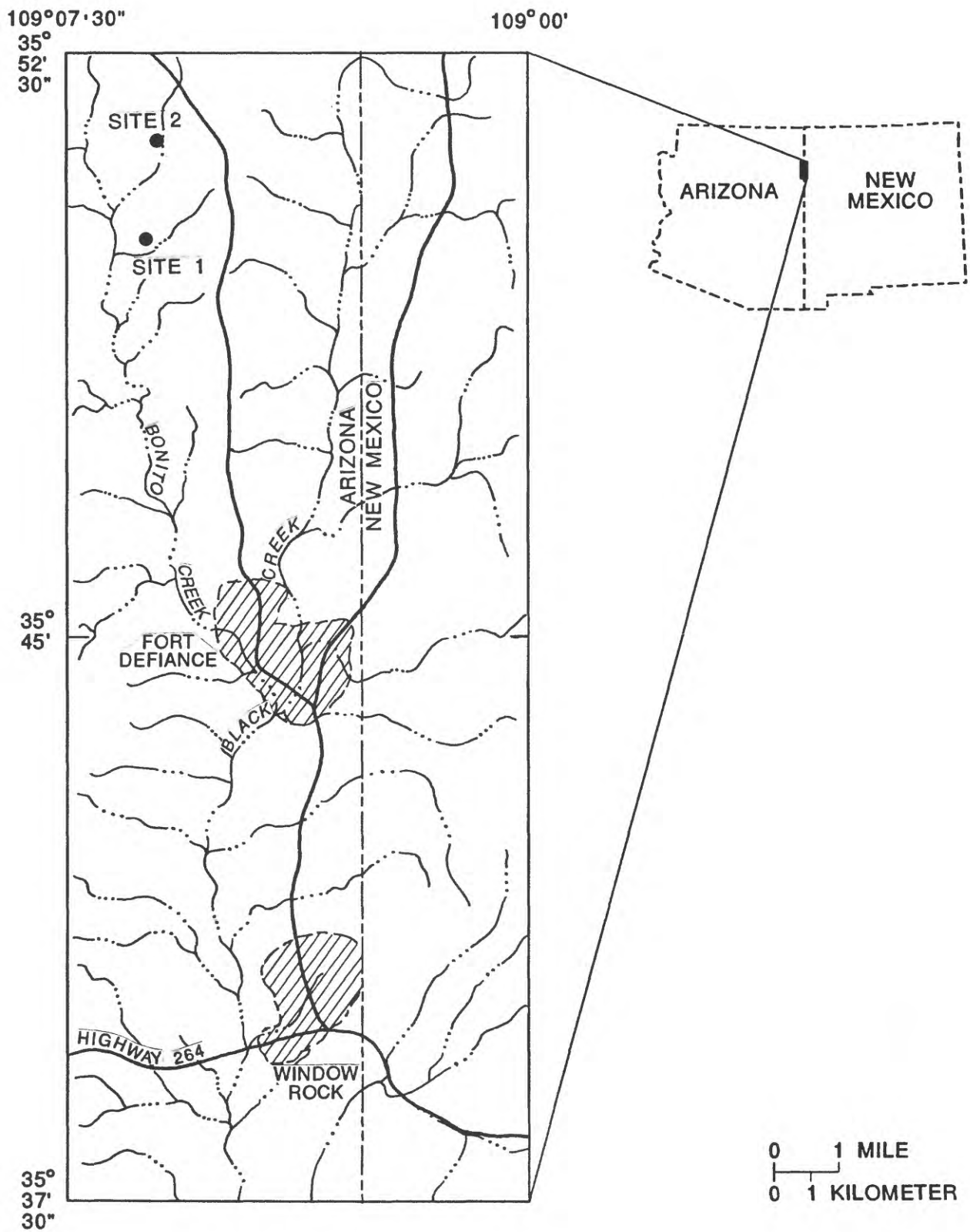


Figure 1.--Location of the study area.



Figure 2.--Vegetation at site 1 near Fort Defiance, Arizona (photograph by Darryl Billie, Navajo Nation Forestry Department).



Figure 3.--Vegetation at site 2 near Fort Defiance, Arizona.

DATA-COLLECTION METHODS AND DATA SUMMARY

Water available for plant growth is supplied by precipitation or is transmitted from adjacent upgradient locations as overland flow or as seepage through the soil. Water leaves the soil and plants through evaporation, transpiration, and transmission to adjacent downgradient locations, either on the land surface or through the soil. The quantities of precipitation, evaporation, transpiration, and pore water within the soil are important for plant growth.

Rainfall, evapotranspiration, and soil-matric potential were monitored using the equipment shown in figure 4. A tipping-bucket rain gage collected rainfall data. Each 0.01 inch (0.25 millimeter) of water caught in the collector sent an electronic signal to the data logger recording the number of tips for each 30-minute interval throughout the day. Micrometeorological equipment used to collect data for calculating evapotranspiration included: (1) upper and lower air-temperature sensors and air intakes for the chilled mirror dewpoint measurement; (2) a net radiometer; and (3) a soil heat-flux plate. A solar panel and a rechargeable, 12-volt battery met the power requirements for the data logger and sensors.

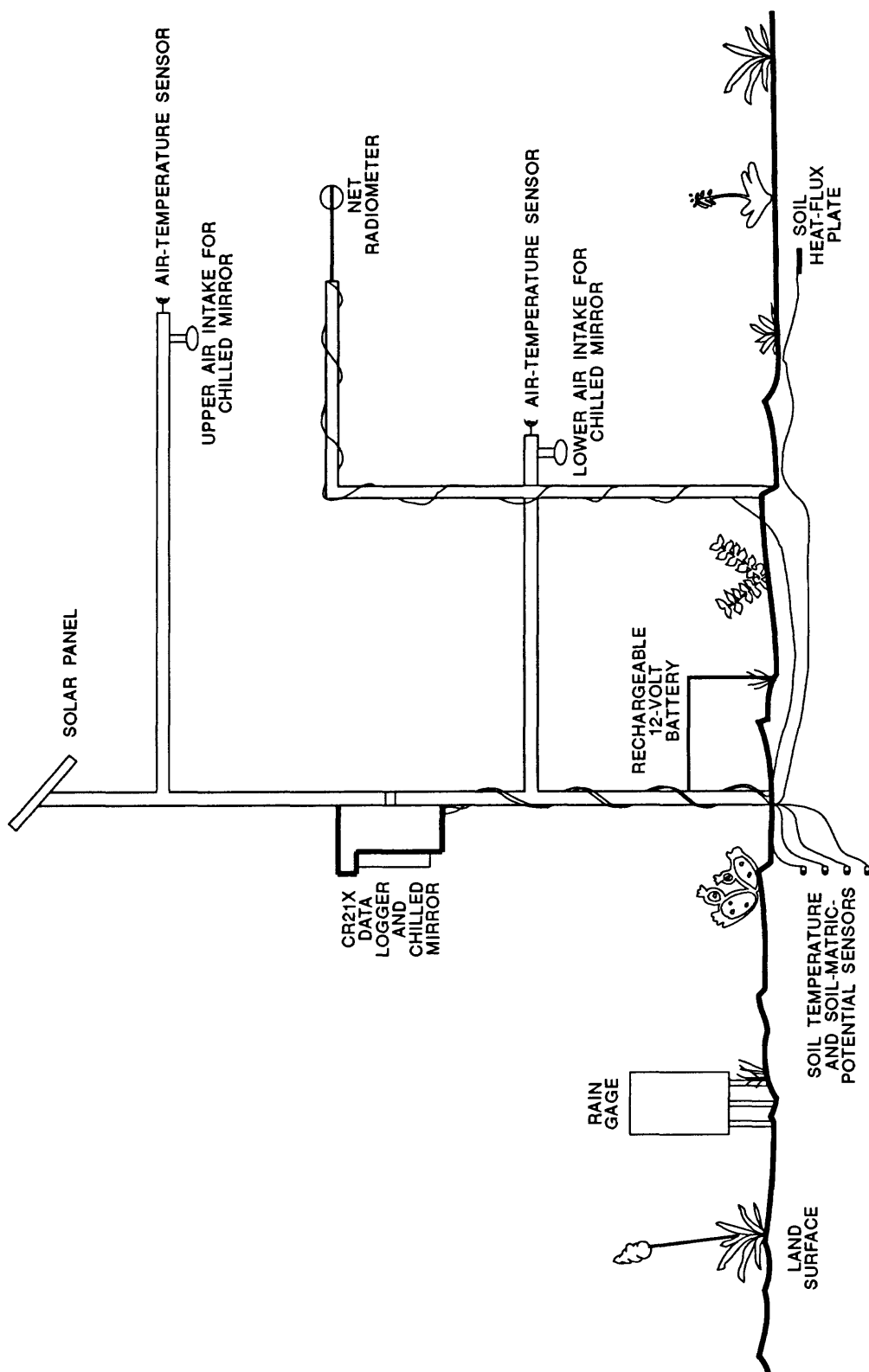


Figure 4.--Instrumentation used for the rainfall, micrometeorological, and soil-matrix-potential data-collection sites.

Rainfall, micrometeorological, soil-water-content, and total soil-water-potential data were collected at frequencies varying from every 20 minutes to twice a year during the 3-year data-collection period 1989 through 1991. Data collected during the warmer part of the year, April through November, included rainfall, evapotranspiration, and total soil-water potential. Data collected during the colder part of the year, November through April, included only total soil-water potential because the tipping-bucket rain gage was not suitable for collecting snowfall and the micrometeorological instrumentation was not suitable for measuring sublimation from snow-covered ground. Volumetric soil-water-content data were collected during November 1990, April 1991, and November 1991. The table below summarizes the frequency and period of record for the data collection.

Site identi- fication	Latitude- longitude	Data collected	Measurement unit of data	Frequency	Period of record
Site 1	35°50'07" 109°06'15"	Rainfall	Inch	30-minute intervals	May 25-Nov. 8, 1989 April 18-Nov. 28, 1990 Apr. 17-Nov. 6, 1991
		Micrometeorology	Millimeter	20-minute intervals	May 25-Nov. 8, 1989 April 18-Nov. 28, 1990 Apr. 17-Nov. 6, 1991
		Soil-water content	Volumetric, in percent	Twice yearly	Nov. 28, 1990 Apr. 18, 1991 Nov. 6, 1991
		Soil-matric potential	Bar	30-minute intervals	May 25, 1989-Nov. 6, 1991
Site 2	35°51'22" 109°06'06"	Rainfall	Inch	30-minute intervals	May 25-Nov. 8, 1989 Apr. 18-Nov. 28, 1990 Apr. 17-Nov. 6, 1991
		Micrometeorology	Millimeter	20-minute intervals	May 25-Nov. 8, 1989 Apr. 18-Nov. 28, 1990 Apr. 17-Nov. 6, 1991
		Soil-water content	Volumetric, in percent	Twice yearly	Nov. 27, 1990 Apr. 17, 1991 Nov. 5, 1991
		Soil-matric potential	Bar	30-minute intervals	May 25, 1989-Nov. 6, 1991

Rainfall

Rainfall is a form of precipitation made of water droplets condensed from the atmosphere and sufficiently massive to fall to the earth. Precipitation includes rainfall and ice particles formed from the atmosphere that fall to the earth in the form of snow or hail. The tipping-bucket rain gage (fig. 4) is designed to collect rainfall only. Rainfall data collected during this study are shown in figures 5-10.

Evapotranspiration

Evaporation is the process by which molecules of water at a water surface or moist soil surface acquire enough energy from sun radiation to escape the liquid state and pass into the gaseous state. Transpiration is the process by which plants lose water to the atmosphere by converting water molecules to the gaseous state at the leaf surface. In many instances evaporation cannot be measured separately from transpiration, hence the two processes are considered together as evapotranspiration (Davis and DeWiest, 1966, p. 18-19).

The evapotranspiration process was not measured directly. Evapotranspiration was calculated from micrometeorological measurements at sites 1 and 2 using the Bowen-ratio, energy-balance method (Arya, 1988, p. 191). As described by Nichols (1991, p. 146-147), this method uses measurements of temperature and vapor pressure of the air at two heights above the sagebrush to determine the ratio of sensible-heat flux (energy that raises the temperature of the air) to latent-heat flux (energy needed for evapotranspiration as latent heat of vaporization). This ratio is defined as the Bowen ratio:

$$\beta = H / \lambda E \quad (1)$$

and

$$\beta = pc_p(T_1 - T_2) / \lambda \epsilon (e_1 - e_2) \quad (2)$$

where

- β = Bowen ratio;
- H = sensible-heat flux, in watts per square meter;
- λ = latent heat of vaporization, in joules per kilogram;
- E = evapotranspiration, in kilograms per square meter per second;
- p = atmospheric pressure, in kilopascals;
- c_p = specific heat of air at constant pressure, in joules per kilogram per degree Kelvin;
- T_1, T_2 = air temperature at heights 1 and 2 above the land surface, in degrees Celsius;
- ϵ = ratio of molecular weight of water to weight of dry air; and
- e_1, e_2 = vapor pressure of air at heights 1 and 2, in kilopascals.

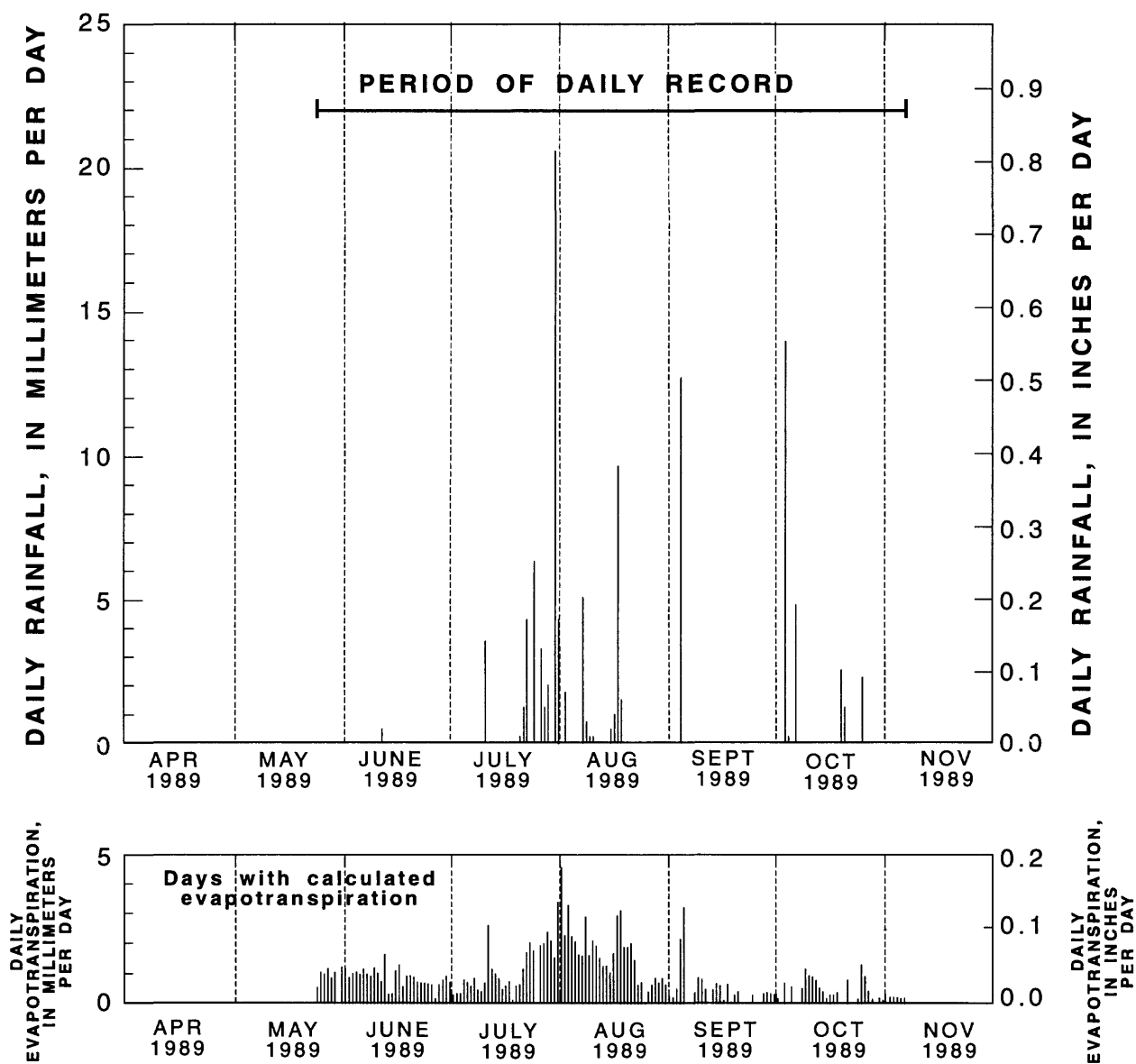


Figure 5.--Daily rainfall and daily evapotranspiration at site 1, May 25-November 8, 1989.

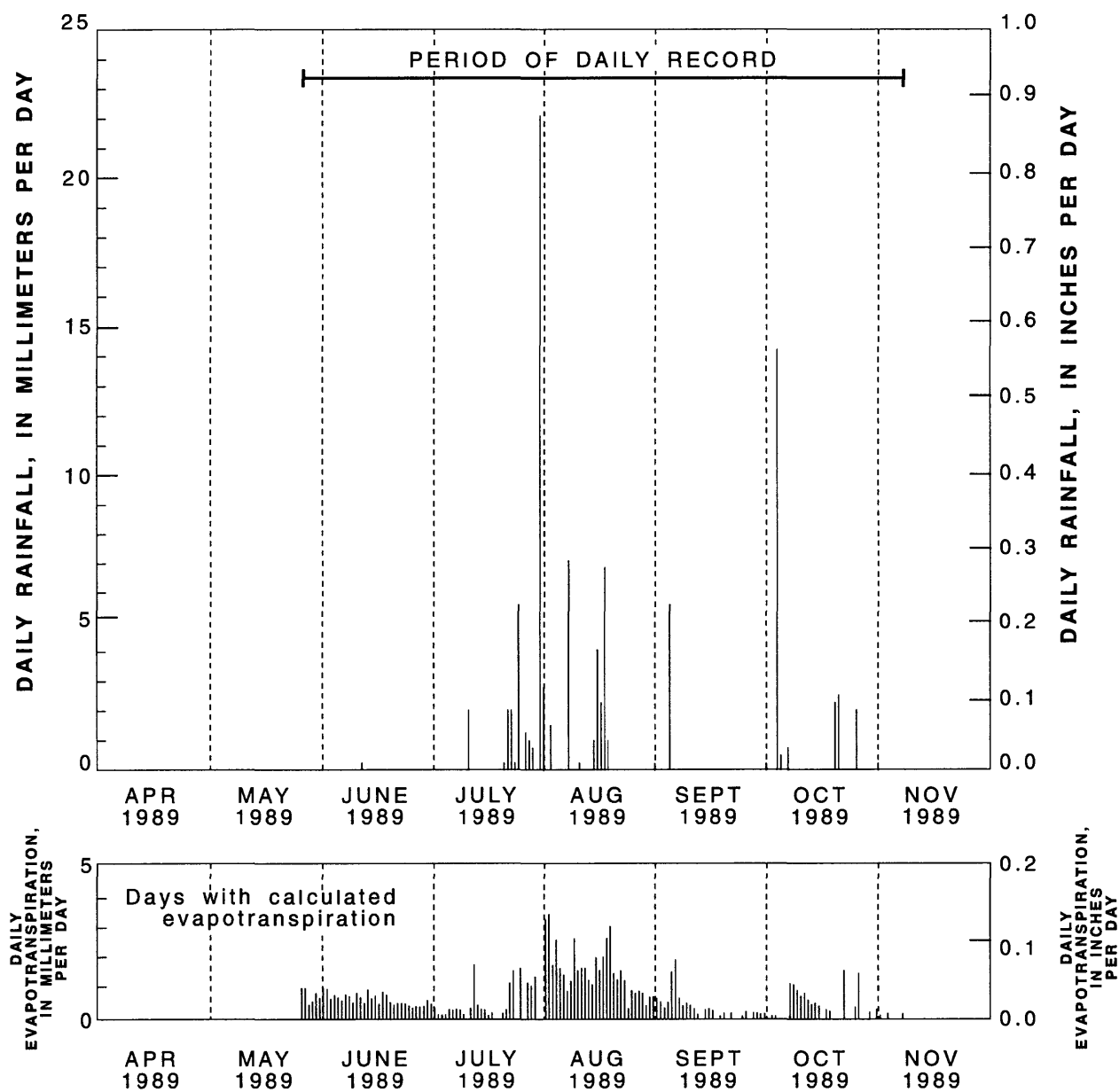


Figure 6.--Daily rainfall and daily evapotranspiration at site 2, May 25-November 8, 1989.

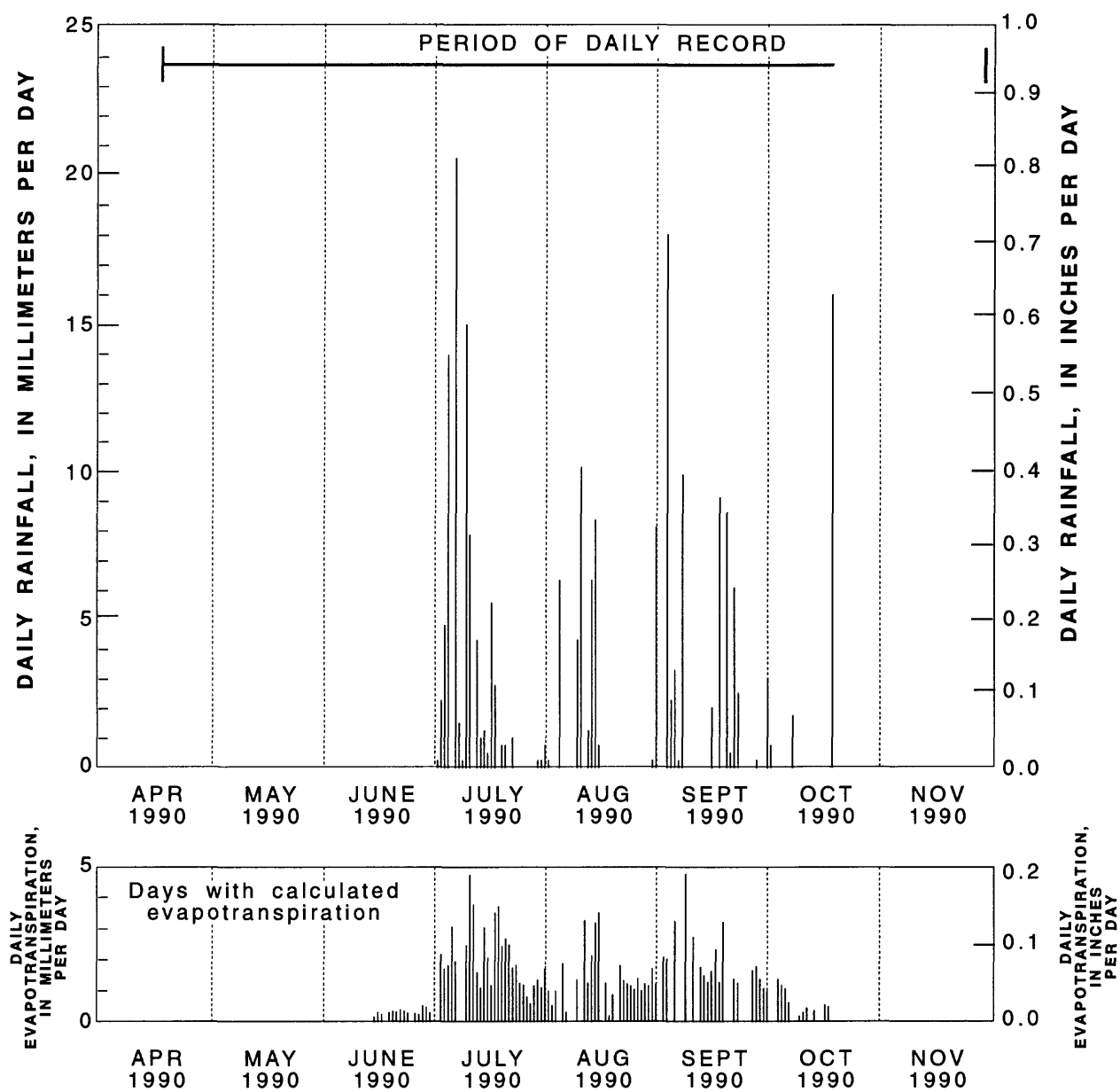


Figure 7.--Daily rainfall and daily evapotranspiration at site 1, April 18-November 28, 1990.

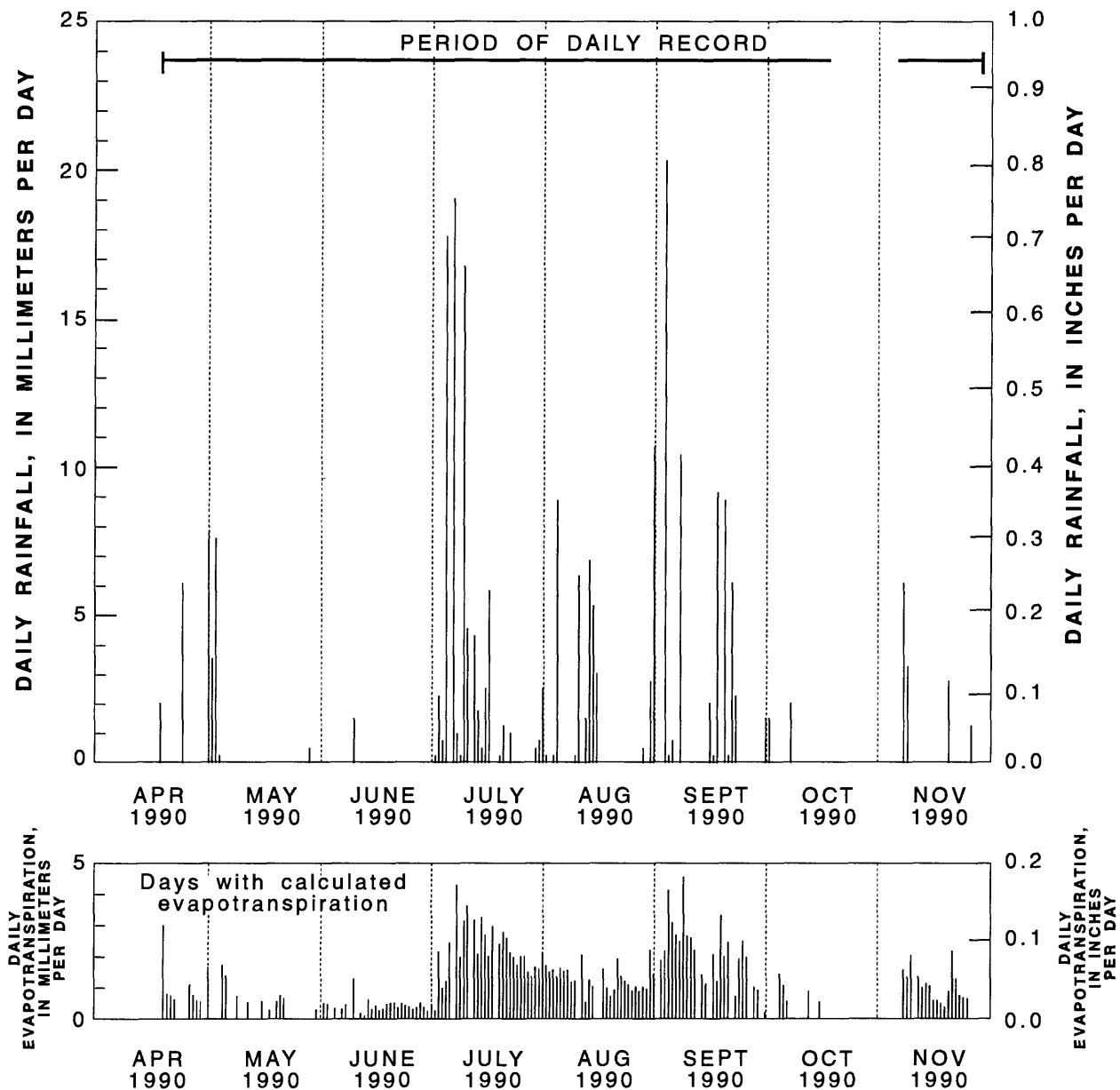


Figure 8.--Daily rainfall and daily evapotranspiration at site 2, April 18-November 28, 1990.

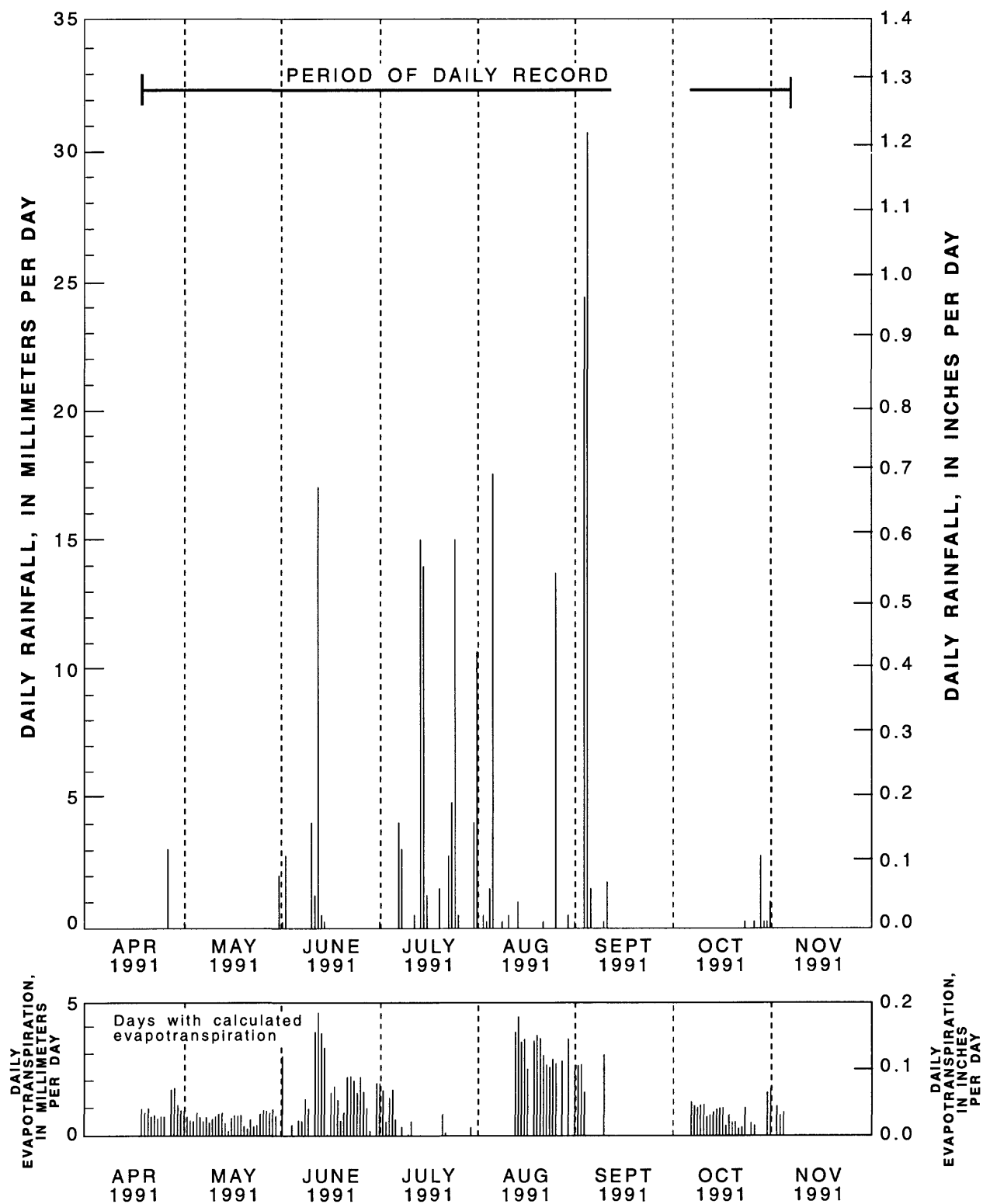


Figure 9.--Daily rainfall and daily evapotranspiration at site 1, April 17-November 6, 1991.

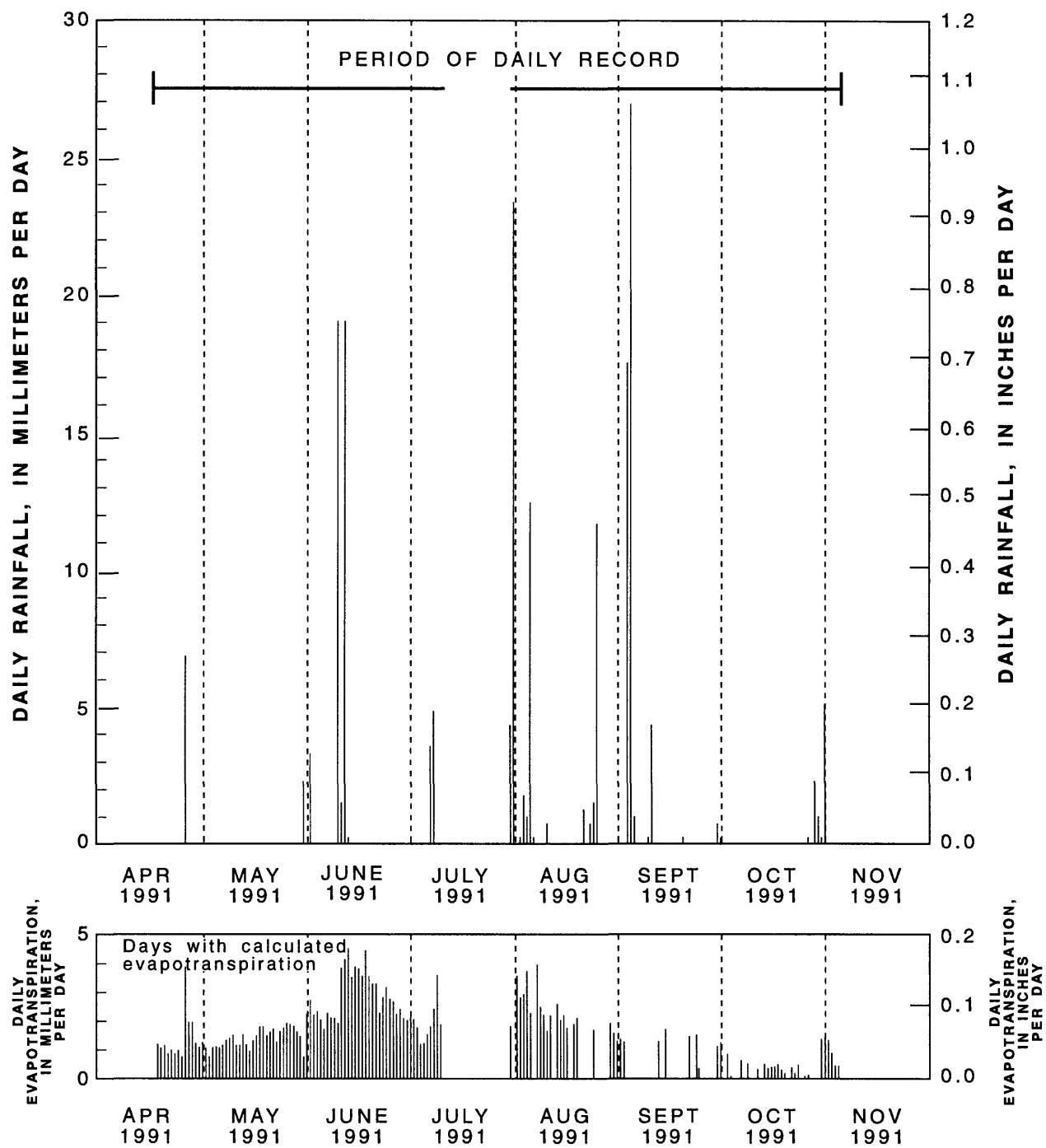


Figure 10.--Daily rainfall and daily evapotranspiration at site 2, April 17-November 6, 1991.

The Bowen ratio, together with measurements of net radiation and soil-heat flux, is used to solve the energy-balance equation, given by

$$\lambda E = R_N - H_G - H \quad (3)$$

Solving equation 1 for H and substituting into equation 3 leads to

$$\lambda E = (R_N - H_G) / (1 + \beta) \quad (4)$$

or solving for E
$$E = \{ (R_N - H_G) / (1 + \beta) \} / \lambda \quad (5)$$

where R_N = net radiation, in watts per square meter; and
 H_G = soil-heat flux, in watts per square meter.

The energy-balance equation applies at an ideal surface. The ideal surface is assumed to be a very thin interface between two media, such as air and sagebrush-covered ground. During the day the sagebrush surface typically receives net radiation from the sun. This energy is converted into sensible heat that warms the air, latent heat that provides the energy for the evapotranspiration process, and heat that is stored in the ground. At night the sagebrush surface typically loses heat energy, but the amount of energy lost is small in comparison to the daytime energy gain. Actual magnitudes of the various components of the surface energy budget depend on many factors, such as the soil-water content, soil texture, geographical location, time of year, time of day, weather (Arya, 1988, p. 11), and vegetation. Vegetation factors are age, health, temperature, and water stress (Stull, 1988, p. 274).

Air temperature and net radiation are measured from sensors mounted on a mast; soil-heat flux is measured by sensors buried in the soil (fig. 4). Vapor pressure is determined from the dew point temperature measured by a chilled-mirror sensor. Air temperature and dew point temperature were measured at 2 and 5.5 feet (0.61 and 1.68 meters) above land surface. Net radiation was measured at 4 feet (1.22 meters) above land surface. Soil-heat flux was measured at 2 to 3 centimeters (0.8 to 1.2 inches) below the land surface. A data logger averaged the sensor measurements, taken every minute, and recorded the averages at 20-minute intervals throughout the day. Difficulties in operation of the chilled mirror arose during continuous 24-hour recording due to an increased need for maintenance and power, and the tendency of the chilled mirrors to ice over at night during the colder months. Logging of the chilled-mirror data was adjusted to take place between the hours of 5:30 a.m. and 8:00 p.m. mountain standard time. The flux of latent heat and sensible heat and, therefore, evapotranspiration was assumed to be zero at night. Figures 5-10 are graphs of the daily evapotranspiration rates from 1989 through 1991.

Temperature-gradient reversals that occur within the first few meters of the Earth's surface at sunrise and sunset or during the passing of a front associated with thunderstorm activity, and measurement of a small vapor-pressure gradient when evapotranspiration rates were small caused computational problems when solving the energy-balance equation with the Bowen-ratio method. The author edited evapotranspiration data for these conditions, replacing erroneous data with a missing-value notation.

Total Soil-Water Potential

As stated by Hillel (1980, p. 134), classical physics recognizes two principal forms of energy: kinetic and potential. Because the movement of water in soil is very slow, its kinetic energy is generally considered to be negligible. The potential energy, which is due to position or internal condition, is of primary importance in determining the state and movement of water in the soil. Differences in potential energy of water between one location or position and another give rise to the tendency of water to flow within the soil. Water moves in the direction of decreasing potential energy. The rate of decrease of potential energy with distance is in fact the force causing flow.

The total soil-water potential is the sum of the gravitational potential, the soil-matric potential, and the osmotic potential (Hillel, 1980, p. 137). The gravitational potential is analogous to the fact that an object tends to fall from a higher to a lower altitude and is determined by the altitude of the point relative to an arbitrary reference level. The soil-matric potential that indicates the water content of the soil pores results from the capillary and adsorptive forces in the soil matrix. The osmotic potential requires a semipermeable membrane to induce liquid flow and differing concentrations on each side of the membrane. Such a situation is found in flow from the soil to the root of a plant, but is not important from one parcel of soil to another. Generally, the total soil-water potential can be determined from the sum of the gravitational potential and the soil-matric potential (Hillel, 1980, p. 147).

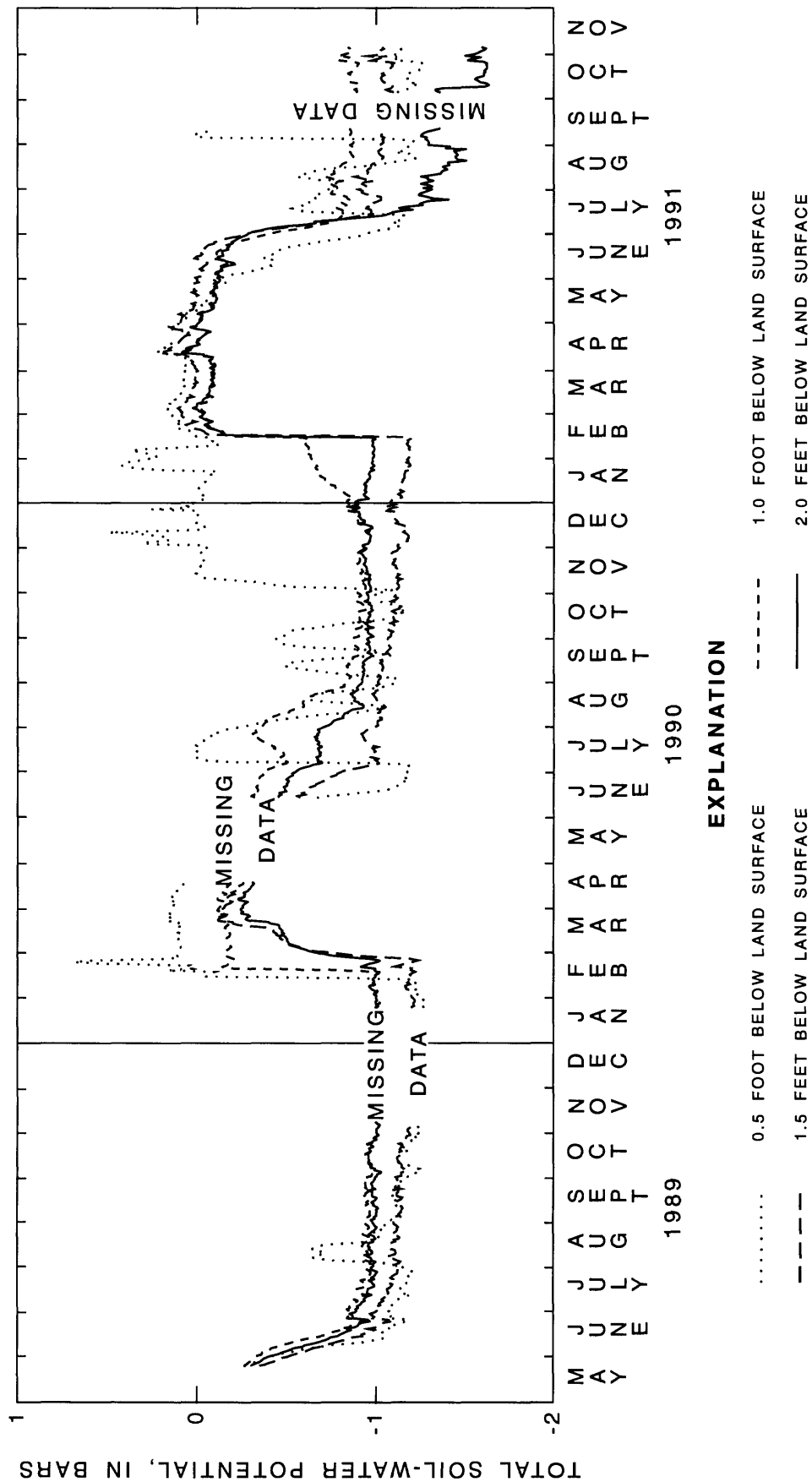
The gravitational potential was small for the 0.5- to 2.0-foot (0.15- to 0.61- meter) differences in altitude between measured points. The reference level for determination of the gravitational potential was the deepest measurement point.

The soil-matric-potential sensors are made of a ceramic material that equilibrates with the soil matrix, measuring the soil-matric potential at the point of burial. The manufacturer calibrates the sensors so that a saturated soil condition would read 0 bar or 0 pound per square inch. An unsaturated soil reads negative, and as the soil becomes more unsaturated or drier, the sensor reading becomes more negative. Calibration of the soil-matric-potential sensors is to -1 bar or -14.5 pounds per square inch. The sensors connect to a data logger to obtain a record at programmed time intervals throughout the day.

Figures 11 and 12 are graphs of the average daily total soil-water potential for each depth monitored at site 1 (0.5, 1.0, 1.5, and 2.0 feet or 0.15, 0.30, 0.46, and 0.61 meter) and site 2 (0.5, 1.0, and 1.5 feet or 0.15, 0.30, and 0.46 meter). At site 2 some total soil-water-potential data were below -5 bars (-72.5 pounds per square inch), indicating that some sensors might have malfunctioned. Although the manufacturer cannot confirm that data below a value of -5 bars were erroneous, the data were replaced with a missing-value notation. Data between -1 and -5 bars (-14.5 and -72.5 pounds per square inch) are useful for observing trends and making comparisons but cannot be considered accurate.

Total soil-water-potential data above 0 bar or 0 pound per square inch were reported at sites 1 and 2 during the period of record. Most of these values occur during winter months. Although values within the soil are expected to be suction values and thus below 0 bar (0 pound per square inch), it is possible that positive values may have originated from the presence of snowpack or ponded water.

The variation in soil-water potential horizontally across the site was not measured and is not known. However, it is expected to be quite variable due to differences in soil texture, soil-water content, plant cover, shading, and drainage.



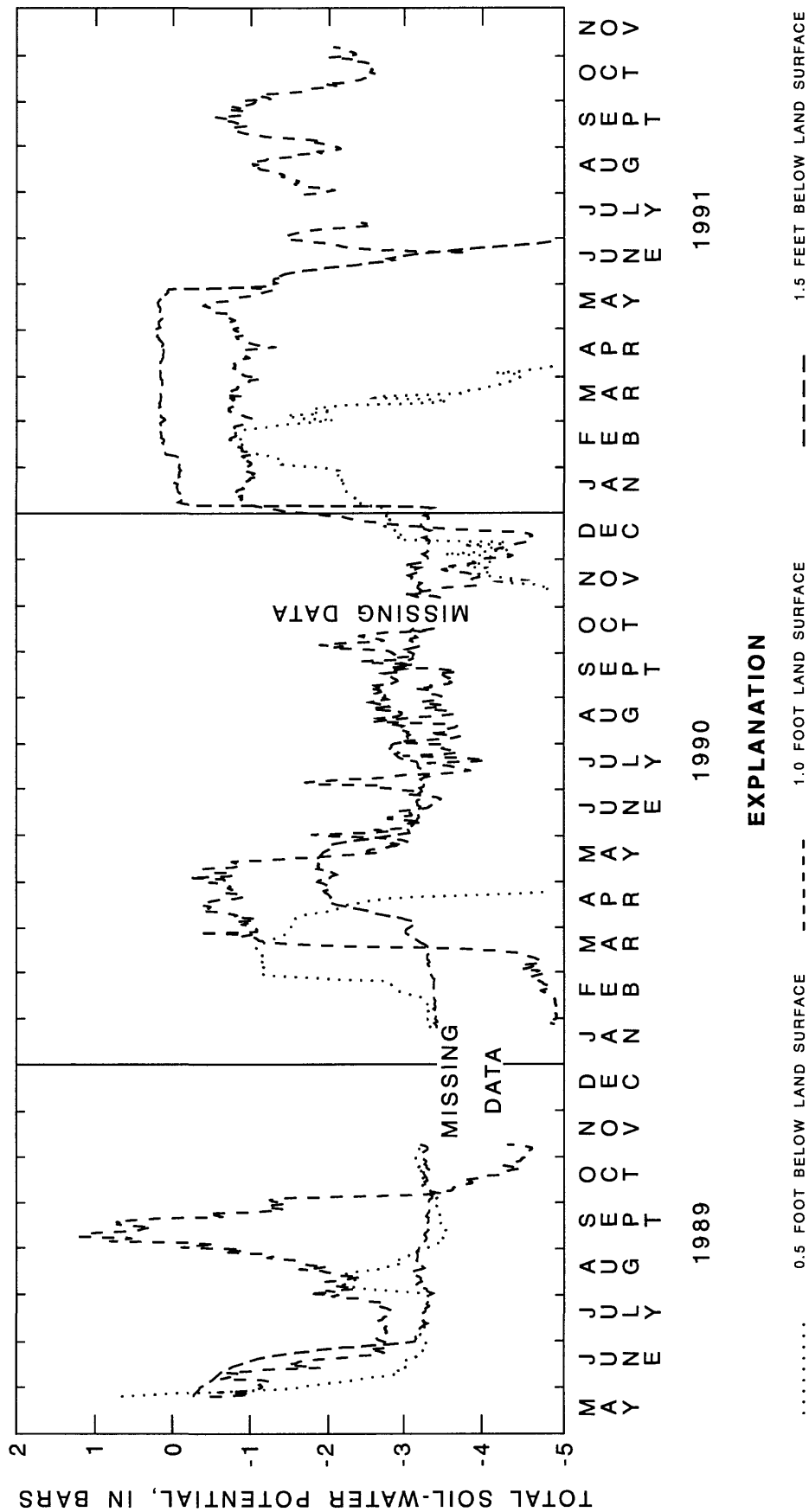


Figure 12.--Daily total soil-water potential at site 2, May 25, 1989, through November 6, 1991.

Soil-Water Content

The volumetric soil-water content or volumetric fractional content of water in the soil indicated whether moisture storage and moisture depletion occurred between data-collection intervals. It is the ratio of water volume to total soil volume. The total soil volume is equal to the sum of the volumes of solids, water, and air. The volumetric soil-water content is multiplied by 100 and reported as a percentage by volume (Hillel, 1980, p. 12-13):

$$\text{volumetric soil-water content} = (\text{water volume} / \text{total soil volume}) \times 100. \quad (6)$$

Soil cores were taken at one-half-foot depth intervals at three locations at each of the two sagebrush sites. Table 1 provides a summary of the volumetric soil-water content measured at sites 1 and 2 during November 1990, April 1991, and November 1991.

Table 1.--Volumetric soil-water content measured at sites 1 and 2, November 1990, April 1991, and November 1991

Site	Date	Distance measured from southwest corner of instru- mentation at site, in feet (and meters)	Depth below land surface, in feet (and meters)	Volumetric soil-water content, in percent
1	November 27, 1990	2 (0.6) south	0.5 (0.2)	24.6
			1.0 (0.3)	15.7
			1.5 (0.5)	33.6
			2.0 (0.6)	22.4
1	November 27, 1990	300 (90) south	0.5 (0.2)	28.3
			1.0 (0.3)	15.2
			1.5 (0.5)	12.4
			2.0 (0.6)	13.4
1	November 27, 1990	300 (90) west	0.5 (0.2)	33.3
			1.0 (0.3)	13.7
			1.5 (0.5)	13.7
			2.0 (0.6)	20.9
2	November 28, 1990	2 (0.6) south	0.5 (0.2)	23.1
			1.0 (0.3)	18.4
			1.5 (0.5)	11.7
2	November 28, 1990	300 (90) south	0.5 (0.2)	19.6
			1.0 (0.3)	11.1
			1.5 (0.5)	11.4
			2.0 (0.6)	9.7
2	November 28, 1990	300 (90) west	0.5 (0.2)	21.6
			1.0 (0.3)	9.9
2	April 17, 1991	2 (0.6) south	0.5 (0.2)	32.1
			1.0 (0.3)	31.6
			1.5 (0.5)	Missing data
2	April 17, 1991	300 (90) south	0.5 (0.2)	65.9
			1.0 (0.3)	44.2
			1.5 (0.5)	42.0
			2.0 (0.6)	37.3
2	April 17, 1991	300 (90) west	0.5 (0.2)	58.2
			1.0 (0.3)	37.5
			1.5 (0.5)	26.8

Table 1.--Volumetric soil-water content measured at sites 1 and 2, November 1990, April 1991, and November 1991--Concluded

Site	Date	Distance measured from southwest corner of instru- mentation at site, in feet (and meters)	Depth below land surface, in feet (and meters)	Volumetric soil-water content, in percent
1	April 18, 1991	2 (0.6) south	0.5 (0.2)	31.1
			1.0 (0.3)	36.3
			1.5 (0.5)	37.8
			2.0 (0.6)	27.6
1	April 18, 1991	300 (90) south	0.5 (0.2)	30.3
			1.0 (0.3)	39.0
			1.5 (0.5)	45.0
			2.0 (0.6)	44.5
1	April 18, 1991	300 (90) west	0.5 (0.2)	29.3
			1.0 (0.3)	32.6
			1.5 (0.5)	34.6
			2.0 (0.6)	29.3
2	November 5, 1991	2 (0.6) south	0.5 (0.2)	9.4
			1.0 (0.3)	8.9
			1.5 (0.5)	10.9
2	November 5, 1991	300 (90) south	0.5 (0.2)	7.5
			1.0 (0.3)	15.7
			1.5 (0.5)	10.7
			2.0 (0.6)	10.2
2	November 5, 1991	300 (90) west	0.5 (0.2)	9.9
			1.0 (0.3)	9.2
			1.5 (0.5)	9.9
1	November 6, 1991	2 (0.6) south	0.5 (0.2)	9.7
			1.0 (0.3)	9.4
			1.5 (0.5)	9.4
			2.0 (0.6)	5.7
1	November 6, 1991	300 (90) south	0.5 (0.2)	16.7
			1.0 (0.3)	17.2
			1.5 (0.5)	20.4
			2.0 (0.6)	5.7
1	November 6, 1991	300 (90) west	0.5 (0.2)	9.9
			1.0 (0.3)	16.9
			1.5 (0.5)	28.3
			2.0 (0.6)	15.9

REPLACEMENT OF VEGETATION AT SITE 1

After the May through November 1989 data-collection season, Navajo Nation Forestry Department personnel replaced the sagebrush at site 1 with four species of grasses and two species of shrubs suitable for livestock grazing. The seeding of site 1 used about 4.7 pounds of seed per acre of land. The combination of seeds was chosen to provide forage for livestock throughout the year. The mixture of seeds and percentage of each seed species is shown in the following table:

Seed mixture	Percentage
Grasses	
Blue grama, Lovington	32
Indian ricegrass	6
Sideoats grama, Vaughan	32
Western wheatgrass, Arriba	10
Shrubs	
Fourwing saltbrush	10
Winter fat	<u>10</u>
	100

The project was completed in stages beginning with clearing and ending with growth as shown in the table below:

Stage	Beginning date	Completion date
Clearing	12/13/89	12/16/89
Plowing	12/17/89	02/28/90
Disking	01/03/90	06/12/90
Harrowing	06/13/90	07/03/90
Seeding	06/13/90	07/03/90
Growth	05/--/91	

Figure 13 shows a visual comparison between the cleared and uncleared land. A noticeable growth of the grasses and shrubs developed at site 1 during the late spring and summer of 1991. Figure 14 shows the grasses and shrubs at the site in August 1991. Growth occurred under conditions of natural precipitation and soil fertility. Site 2 continued to serve as a basis for comparison with the replacement-vegetation site.



Figure 13.--Cleared land at site 1 (right) compared to adjacent sagebrush (left)
(photograph by Darryl Billie, Navajo Nation Forestry Department).



Figure 14.--Establishment of grasses and shrubs at site 1.

FACTORS AFFECTING GROWTH OF REPLACEMENT VEGETATION

Grasses and shrubs seeded in June and July 1990 attained a healthy growth by August 1991 (fig. 14). Factors that may have contributed to the growth of the replacement vegetation include precipitation, evapotranspiration, soil-water content, and topography.

Rainfall data (figs. 5-10) collected during this study and annual precipitation data from U.S. Department of Commerce (1989, 1990, and 1991) climatic records show that 1990 and 1991 were wetter years than 1989:

Year	Rainfall April-November		Precipitation January-December	Days of record		
	Site 1	Site 2	Window Rock	Site 1	Site 2	Window Rock
1989	4.19 inches (106 millimeters)	3.64 inches (92 millimeters)	6.42 inches (163 millimeters)	168	168	365
1990	8.53 inches (217 millimeters)	9.43 inches (240 millimeters)	12.6 inches (320 millimeters)	128	206	365
1991	8.18 inches (208 millimeters)	7.09 inches (180 millimeters)	13.4 inches (340 millimeters)	181	186	365

Evapotranspiration information summarized below from data collected during this study (figs. 5-10) shows that evapotranspiration was generally greater during 1990 and 1991 when precipitation was greater:

Year	Evapotranspiration		Days of record	
	Site 1	Site 2	Site 1	Site 2
1989	145 millimeters (5.71 inches)	110 millimeters (4.33 inches)	146	136
1990	143 millimeters (5.63 inches)	203 millimeters (7.99 inches)	98	148
1991	163 millimeters (6.42 inches)	241 millimeters (9.49 inches)	124	139

Rainfall rates and evapotranspiration rates were similar for site 1 and site 2. Rainfall rates during the April through November 1989-91 data-collection period ranged from 0 to 1.21 inches per day (0 to 30.7 millimeters per day) at the two sites. Evapotranspiration rates during April through November 1989-91 are generally between 0.5 and 2 millimeters per day (0.02 to 0.08 inch per day) for both sites (figs. 5-10). After rainfall, evapotranspiration rates rise to about 2 to 5 millimeters per day (0.08 to 0.20 inch per day) (figs. 5-10). When rain falls, most of the energy from net radiation goes into evapotranspiration (latent heat) instead of heating the air (sensible heat) (fig. 15). The energy used for instantaneous evapotranspiration (latent heat) follows a bell-shaped daily variation for both sites.

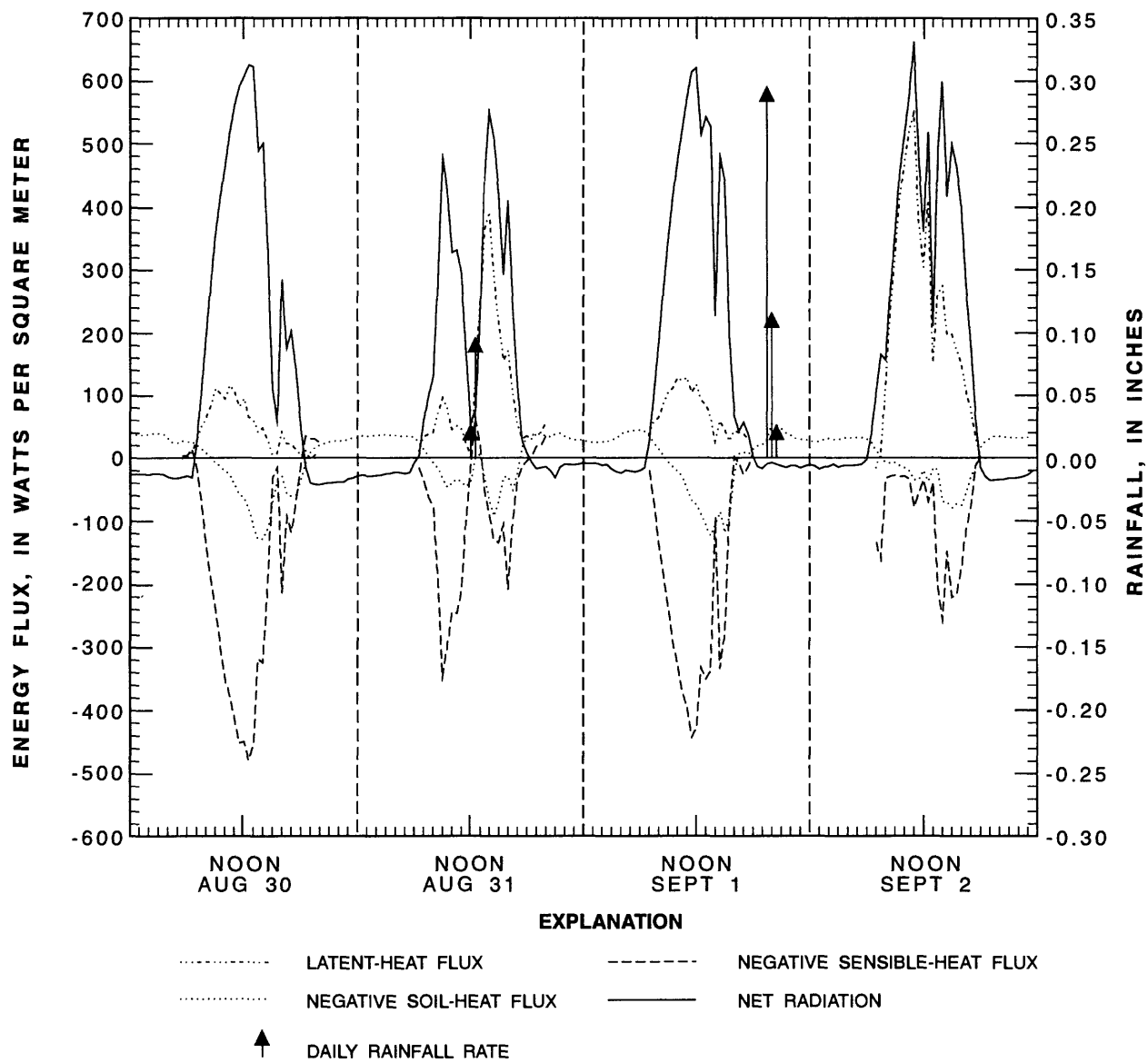


Figure 15.--Energy balance and daily rainfall at site 2 near Fort Defiance, Arizona, August 30-September 2, 1990.

The vertical, total soil-water-potential profiles at sites 1 and 2 (figs. 11 and 12) indicated wetting from snowmelt during the spring and drying during the summer. Unmeasured precipitation in the form of rain and snow added water to the soil during the winter months. Decreased evapotranspiration during winter months contributed to the retention of soil water. The total soil-water potential at site 1 generally ranged from -2 to 0 bar (-29 to 0 pound per square inch) (fig. 11). The total soil-water potential at site 2 generally ranged from -4 to 0 bar (-58 to 0 pound per square inch) (fig. 12). The potential due to gravity was small and ranged from 0.015 to 0.045 bar (0.218 to 0.652 pound per square inch) for the 0.5- to 2.0-foot (0.15- to 0.61-meter) differences in altitude. Therefore, the total soil-water potential was dominated by the soil-matric potential. The total soil-water potential indicates that the soil at site 1 was wetter than at site 2.

The volumetric soil-water-content analyses (table 1) showed that soil-water content was greater in April after winter precipitation than in November after summer heat caused drying of the soil. At sites 1 and 2 soil-water content ranged from 26.8 to 65.9 percent in April and 5.7 to 33.6 percent in November. At site 1 on November 27, 1990, volumetric soil-water content ranged from 12.4 to 33.6 percent at three locations and four depths at each location (table 1). At the same site on April 18, 1991, volumetric soil-water content ranged from 27.6 to 45 percent for the same three locations and four depths (table 1). Between the end of November 1990 and the beginning of April 1991 soil-water content increased at site 1. This increase in soil-water content contributed to the germination of seeds and growth of plants.

The limiting quantity of precipitation and soil-water content needed for germination and growth of the replacement vegetation is not known. However, the rainfall of at least 8 inches (203 millimeters) during April through November 1990 and April through November 1991 and a volumetric soil-water content of 12.4 to 45 percent were sufficient for germination and growth at site 1.

The topography at site 1 may contribute to the growth of the replacement vegetation. Because site 1 is located within a slight topographic depression, surface drainage may collect and this site may also provide a sheltered setting for seed germination and plant growth. The aspect at both sites is easterly.

SUMMARY

The Navajo Nation Forestry Department cleared sagebrush from site 1 near Fort Defiance, Arizona, during December 1989 and seeded the site with four species of grasses and two species of shrubs during June and July 1990. A healthy growth of grasses and shrubs developed at the site by August 1991. The growth occurred under conditions of natural precipitation and soil fertility. Average precipitation at the Window Rock, Arizona, climatological-data station is 11.51 inches per year (292.4 millimeters per year). Precipitation at Window Rock during 1990 and 1991 was 12.6 and 13.4 inches per year (320 and 340 millimeters per year), respectively.

Rainfall rates and evapotranspiration rates were similar for site 1 and site 2. Rainfall rates during the April through November 1989-91 data-collection period ranged from 0 to 1.21 inches per day (0 to 30.7 millimeters per day) at the two sites. Evapotranspiration rates generally ranged from about 0.5 to 2 millimeters per day (0.02 to 0.08 inch per day). Higher evapotranspiration rates of about 2 to 5 millimeters per day (0.08 to 0.20 inch per day) occurred after the ground was wetted by summer rainfall.

Total soil-water-potential data and volumetric soil-water-content data indicated a difference in wetness due to seasonal variation. Soils were wetter at both sites in April after winter snowmelt than in November after summer drying. The total soil-water potential at site 1 generally ranged from about -2 to 0 bar (-29 to 0 pound per square inch). The total soil-water potential at site 2 generally ranged from about -4 to 0 bar (-58 to 0 pound per square inch). Volumetric soil-water content at the sites ranged from 5.7 to 65.9 percent.

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