UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EVAPOTRANSPIRATION FROM FORAGE GRASS REPLACING NATIVE VEGETATION IN THE GILA RIVER VALLEY OF ARIZONA

By O. E. Leppanen

U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 81-1018

NSTL Station, Mississippi

1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Doyle G. Frederick, Acting Director

For additional information write to:

U.S. Geological Survey, WRD
Gulf Coast Hydroscience Center
Building 1100
NSTL Station, MS 39529

CONTENTS

ILLUSTRATIONS

TABLE

CONVERSION TABLE: Metric units to inch-pound units

Multiply	By	To Obtain
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
meter per second (m/s)	2.237	mile per hour (m/h)
degree Celsius (°C) + 17.78	1.8	degree Fahrenheit (°F)

In the conversions below, calorie means gram calorie

calorie per square centimeter minute (cal/(cm^2 min))	221.2	British thermal unit per square foot hour (Btu/(ft^2 h))
calorie per square centimeter minute degree Celsius (cal/(cm^2 min °C))	122.9	British thermal unit per square foot hour degree Fahrenheit (Btu/(ft^2 h °F))

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 mean sea level.

NGVD of 1929 is referred to as sea level in this report.

EVAPOTRANSPIRATION FROM FORAGE GRASS REPLACING NATIVE VEGETATION IN THE GILA RIVER VALLEY OF ARIZONA

By O. E. Leppanen

ABSTRACT

Estimates of evapotranspiration from an area of forage grass, which had been planted to replace native vegetation of little economic value, were made daily for a 363-day period in 1969 and 1970. The measurement site was located in the Gila River valley in east-central Arizona. The forage, panicgrass (Panicum antidotale Retz.), grew from seed during the early summer of 1969 and after winterkill, regrew in 1970. Daily evapotranspiration estimates, which were based on energy budget measurements, ranged from a maximum of 9.2 millimeters to small amounts of condensation. Two daily values of substantial condensation (0.9 and 0.4 millimeter) were of dubious quality, but were retained in the record. The annual evapotranspiration was 989 millimeters, of which about 332 millimeters came from precipitation at the site. The water table fluctuated between 210 and 280 centimeters below land surface. However, the measurement site was near a wash, so that undocumented, shallower subterranean flows may have occurred.

INTRODUCTION

During a large-scale hydrologic study in Arizona, data were needed to compare evapotranspiration from areas before they were cleared of existing vegetation, with evapotranspiration after clearing and replanting. This report briefly describes how daily estimates of evapotranspiration from a revegetated site were made, and lists them for a 363-day period from June 19, 1969, to June 16, 1970.

The large-scale hydrologic study was the Gila River phreatophyte project (Culler and others, 1970) conducted in east-central Arizona, the location of which is shown in figure 1. The solid diamond symbol near the right edge of figure 1 adjacent to cross section 3 indicates the location of the study site described in this report. The original cover of halophytic vegetation was of little economic value, consisting largely of seepweed (*Suaeda depressa* Wats.) and iodinebush (*Allenrolfea occidentalis* Wats.) as described by Turner (1974). Saltcedar (*Tamarix chinensis* Lour.) had grown in areas adjacent to the nearby Gila River channel. The replacement vegetation was panicgrass (*Panicum antidotale* Retz.) considered to be acceptable forage.

Daily evapotranspiration estimates made at the panicgrass study site were based on direct energy budget measurements. Modifications were made to the direct energy budget technique when results were unsatisfactory. When water-vapor data were unusable or missing, convected heat was estimated using a set of empirical functions in order to apply the energy budget. Interpolation methods were developed to estimate daily evapotranspiration when daily data were

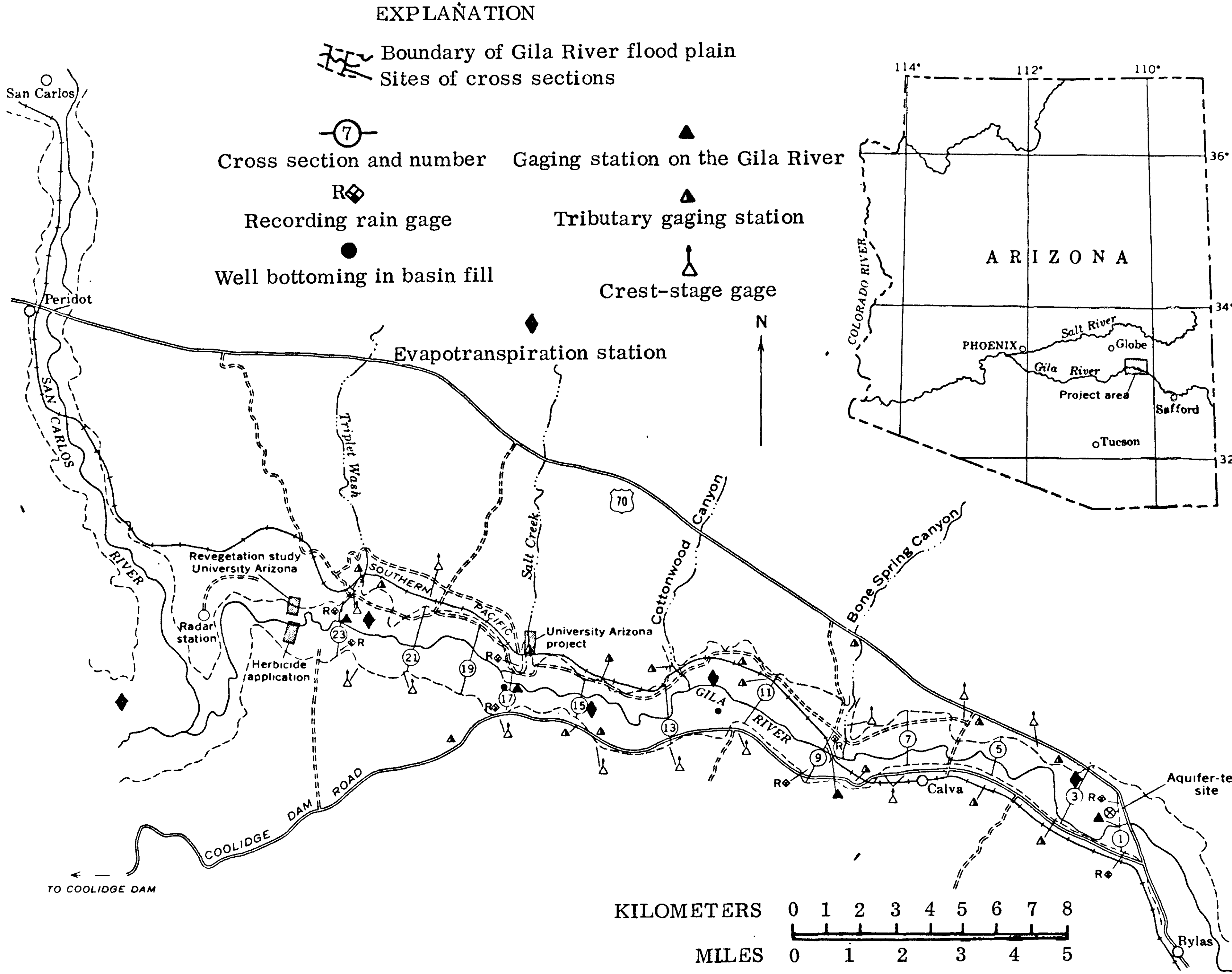

Figure 1.— Project area and instrumentation location.

completely missing. These interpolation methods were based on data from a National Weather Service (NWS) station nearby. Details of the site, water available for evapotranspiration, instrumentation needed to gather basic data, and data analyses are also briefly described.

SITE

The site at which evapotranspiration determinations were made was upon an alluvial fan with a very gentle slope (1:230) toward the southwest. (In the Gila River phreatophyte project orientation scheme, the location was designated 3R3.) A 9-m tall instrumentation mast was erected at the site. The channel of the Gila River, meandering northward in its flood plain, lay about 450 m west of the mast. To the south, the river channel was 1 km distant. U.S. Highway 70 is about 250 m northeast of the site (fig. 1). The highway, at its closest approach, had a grade level 0.6 m above the site altitude of 782 m above sea level (NGVD of 1929).

Excepting the relatively minor obstructions offered by the highway grade level and the Gila River channel depression, the wind fetch was clear for at least 1 km in all directions.

A small wash discharged through culverts near the point where the highway was closest. Although the ill-defined wash channel ran some distance east of the site, its gradient was so gentle that local flooding could occur.

The area has a desert climate. The 10-yr normal annual temperature at the NWS station at Coolidge Dam (San Carlos Reservoir), located about 32 km downstream from the site, was 19.7°C (Celsius). Monthly normal temperatures ranged from 30.6°C in July to 7.7°C in January. The 10-yr annual normal precipitation at the NWS station was 349 mm; pan evaporation was 2,386 mm.

During the 363-day measurement period 332 mm of rain fell at the site (no snow, hail, or sleet was observed). The monthly distribution of rainfall differed considerably from the NWS normals, ranging from a deficit of 38 mm in January 1970 to an excess of 90 mm in March 1970. The summer monsoon season was timely, however, beginning on July 10, 1969.

The location of the site was determined by the vegetation present. The area around the mast had been cleared of vegetation in previous years (1966-1968) and panicgrass seed was planted in the early spring of 1969. Before the replacement grass became established in July 1969, there was a substantial infestation of weeds, largely Russian-thistle (*Salsola kali*), along with regrowth of the area's original vegetation, mostly seepweed and iodinebush. Figures 2A and 2B are low-level aerial photographs of the area around the measurement site taken in May 1969 before the replacement grass had grown substantially. By mid-August 1969 most of the grass was about 1 m tall, later attaining its maximum height of about 1.3 m. The growth was uneven and spotty, but the area around the measurement point was reasonably uniform for about 100 m in all directions. Figure 3 is a photograph showing the panicgrass in August 1969 and the lower part of the instrument mast with three of the four aspirated psychrometers described in the section

Figure 2A.--View to south-southeast of area planted to grass before substantial growth. Arrow points to top of instrument ma

Figure 2B.--View to the south from higher altitude. Note irregular nature of planting. Instrument shack and propane tank visible to right of mast (arrow).

Figure 3.--Panicgrass growth in August 1969. Stadia rod is calibrated in feet. Three aspirated psychrometers on mast point to the north, and are mounted 1, 2, and 4 meters above ground surface.

on instrumentation. The area seeded to grass extended from the highway to the Gila River channel, and about 300 m to the southeast of the measurement point.

By late November 1969 all the grass (and weeds) had been frost-killed, with only basal leaf rosettes remaining green. By the end of November settling of the dead grass was complete, leaving a mat of perhaps 0.3-m thickness.

In 1970, ample spring rains in March fostered an early growth of weeds that reached a height of about 1 m by mid-April. The hot weather of May and June allowed the replacement grass to overtake the weeds, reaching a height of 1 m by mid-June.

No mechanical or chemical analyses of the soil were made. The surficial alluvial sediments are relatively shallow; during installation of instrumentation into 8-cm-diameter holes located 3 m north and south of the instrument mast, lenses of sand or gravel were found at several depths between 90 cm and 160 cm. The proposed 200-cm depth of these holes could not be attained by hand augering, apparently because of cobbles. However, a neutron-meter soil-moisture measurement access tube was successfully installed to a depth of 350 cm about 8 m west of the instrument mast. Local pedology is uncertain; the site area apparently was one with a complex distribution of rock and soil materials of varying sizes in patterns typical of desert washes.

WATER AVAILABLE FOR EVAPOTRANSPIRATION

The water available for evapotranspiration came from rain, runoff spreading from the nearby wash, soil moisture from the capillary fringe overlying the shallow water table, and possibly from localized ground water perching or mounding.

Rainfall, which was slightly below normal during the observation period, was measured with a nonrecording gage at the site. The record was complete, except for a period near the end of March 1970 when all instrumentation was inoperative. Soil-moisture observations made on March 27 and April 3, 1970, showed a substantial increase in water stored in the top 30 cm of soil. From these data, and from nearby rain gage records, a rain of about 30 mm was inferred to have fallen on March 29.

Runoff from the nearby wash possibly occurred on five occasions. However, ponding was visually observed only once; the other four runoff events were deduced from the effects upon soil temperature measured 2 cm below the ground surface and from nearby rainfall records. Some uncertainty remained about two of these four runoff events because of power failures. Two moderate runoff adjustments were made to the daily rainfall record for April 3 and April 4, 1970, based on shallow soil-moisture observations on March 27, April 3, and April 10, 1970. The other two runoff events, both occurring during winter, were apparently minor and rainfall records were not adjusted.

Soil-moisture readings were taken with a neutron-scattering meter in an access tube about 8 m from the instrument mast. Observations were made at approximate weekly intervals at depths of 10, 41, 71, 102, 132, 223, 254, 284, and 315 cm, beginning on July 25, 1969, and extending into August 1970. Data for the 36 days between the initiation of energy budget measurements on June 19, 1969, and the first soil-moisture readings were estimated from soil-moisture readings and depth-to-water observations at an access tube and observation well located about 350 m ESE of the mast.

There was no observation well at the site, so the depth to water was determined from the soil-moisture readings. The water table level fell from 265 cm on June 19, 1969, to a depth of 285 cm on August 20, 1969, and then rose continuously until May 15, 1970, when the water table reached a level of 205 cm below land surface. The level then fell to a 235-cm depth at the end of the observation period.

Several anomalies, not due to instrument malfunctions, were present in the soil-moisture data. These confirmed that the near-surface pedologic conditions were far from uniform and that flow occurred in the unsaturated zone below the surface. An example can be drawn from the data at the access tube 350 m from the site, where no rain fell in June 1969. After gradually declining to 15 percent by volume on June 14, the soil-moisture content at 183-cm depth rose very rapidly to 38 percent on June 23. The soil-moisture fraction then fell, somewhat more slowly than it rose, to 24 percent on July 23, 1969. The water table at a paired observation well about 1 m from the access tube was at a depth of about 310 cm during these soil-moisture changes, and was continuously falling.

The depth of root penetration by the vegetation was not ascertained. However, because most of the vegetation grew anew each spring, soil-moisture depletion by roots was thought to be small at depths below 1 m. Except during two periods of infiltration, soil-moisture contents at the 71-, 102-, and 132-cm depths at the site were statistically constant (at the 0.95 significance level) over the observation period with very low average values of 11.00, 7.09, and 7.62 percent by volume, respectively. The soil-moisture content at the 71-cm depth did, however, exhibit a small but regular increase over the 363-day observation period, and the content at 132 cm increased slightly from January through June 1970.

INSTRUMENTATION

Accurate instruments are needed when measuring evapotranspiration by a direct application of an energy budget. Over long study periods, the instrumentation must also be rugged and reliable, especially if it must operate unattended. The limits of accuracy and precision of common meteorological instruments are often approached. No standardization exists and specially designed devices are often used. In this study the instrumentation was designed to operate unattended for periods of up to 2 weeks.

Energy budget studies require measurement of thermal fluxes into, out of, and within the physical system considered. For a transpiring canopy of vegetation, variables which must be considered are: net radiant heat flux above the canopy; vertically convected sensible and latent heat flux above the canopy; horizontally advected heat flux above the canopy; horizontally advected heat flux into, within, or out of the canopy; conducted heat flux below the canopy; and changes in heat stored in the canopy. Stored heat varies with the mass of the canopy system as well as with its temperature, so changes in mass occasioned by rain and evaporation or by canopy growth or decay must be considered also. In this study the word canopy includes not only above-ground foliage but also a part of the supporting soil, in order to account for evaporation from the soil.

Net radiant heat flux (net radiation) was measured with a ventilated thermopile flat-plate radiometer that was commercially available. It was mounted facing solar south, 3.5 m out from the 9-m tall instrument mast, at an elevation of 4 m. This elevation above the canopy had an integrating effect on the radiometer vision, as the effect of patchiness in the vegetation canopy tended to be averaged. Radiative diffusion was not deemed to be a problem. The exposed flat-plate sensor of the radiometer was washed with distilled water during every service visit. The plate was resurfaced five times during the observation period and the radiometer calibration checked after four of the resurfacing paintings. The calibration checks were made using a shading technique and showed a consistent bias toward a calibration coefficient smaller than that given by the manufacturer. The differences, however, were small (the largest was 6 percent) and they depended upon the calibration of short-wave radiometers and recorders. Hence the calibration furnished by the manufacturer was used for computations. Net radiation was measured once every 12 minutes.

Convected heat estimates and latent-heat transport computations depended upon temperature and water-vapor pressure gradients above the canopy. Needed temperature measurements were made at elevations of 1, 2, 4, and 8 m above the ground surface, using identical specially fabricated wet- and dry-bulb psychrometers. These shielded psychrometers used 30-gage copper-constantan wire thermocouples for sensors, each ventilated by an air flow with velocity between 2 and 3 m/s. An air flow of about of about 0.5 m/s was apparently sufficient for full depression of the wet bulbs, even under the extremely dry conditions often encountered. Air flows at the four psychrometers were equalized by adjusting gate valves in the plastic tubing connecting each psychrometer to a vacuum manifold. A specially made heated-thermistor device was used to make velocity comparisons. Reproducibility of temperature values was ±0.1°C and accuracy about ±0.25°C. Occasionally, simultaneous and temporary drifting of all temperature values reduced accuracy up to +0.5°C but this had little effect upon computations. Wet- and dry-bulb readings were frequently checked against readings taken with an Assman-type psychrometer at each elevation. Each psychrometer temperature was recorded once every 24 minutes.

Despite the careful design and operation of the psychrometry, the validity limits of the technique were often approached or exceeded. In winter, for example, when the daily average vapor pressure at each elevation was sometimes below 4 millibars (one millibar equals 100 Pascals) and evapotranspiration very small, routine computations were meaningless because of imprecision in the temperature values that were tabulated to the nearest 0.1°C.

No measurements were made to evaluate advected heat directly. The experimental area was considered large enough and the surface uniform enough to result in semistable 4-h average temperature profiles in the vegetation and above it. Net advection by air would be negligible. Net advection by water was also small.

Heat-flow measurements in the soil were made with two commercial flat-plate heat-flux meters buried at a 50-cm depth. The plates were located 3 m north and south of the 9-m tall instrument mast. The accuracy of calibration of the plates was uncertain because they had been used previously. Even so, a calibration error of ±20 percent would have had no significant effect on evapotranspiration computations. The output from each plate was recorded once every 24 minutes.

Required temperature measurements for heat storage computations were made with thermocouples buried at 2-, 50-, and 100-cm depths at the same locations as the heat-flow plates. The 1-m air temperature value was also used. Each temperature was recorded once every 24 minutes and had the same accuracy as the air measurements. Thermal mass changes in the ground were accounted for by changes in soil moisture that were measured with a nuclear soil-moisture meter. Rain at the site was measured with a nonrecording wedge gage mounted on a nearby recorder shack. Vegetation mass estimates were made when required.

All measurement values were printed upon strip charts by a modified Honeywell Model 15[1/] recorder. A parallel recording system for punching data into paper tape was also used, but was unreliable. Power was supplied by a small propane-fueled motor-generator. Malfunction of the powerplant was a principal cause of missing data.

The instrumentation performed adequately, but resulted in 24 percent (87 days) of the records being totally missing, or with data too fragmentary to yield a daily evapotranspiration value. The winter period from November 18, 1969, to February 28, 1970, had the worst data yield with 36 percent of the days missing. Of the 37 winter days missing, 34 were consecutive, from January 11 to February 13, 1970. Freezing of the wet bulbs resulted in some missing data; supercooling of the capillary water in the wicks often could not be distinguished from icing.

The instrument mast was the only tall structure in the treeless area. Bird droppings on the radiometer were often found and nest building in the psychrometers occurred. Range cattle damaged wiring and the 1-m aspirator piping. Weather damage, winds and flooding, and animal damage accounted for approximately one-third of the missing data.

[1/] The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

INITIAL DATA REDUCTION

Eighteen meteorological variable values plus three reference values were printed on strip charts by the 24-channel recorder at the rate of one value per minute. Time corrections, which were sometimes needed because of generator speed variations, were made. The data were then grouped manually and transcribed into six daily 4-h averages based on mean solar time. After converting to physical quantities and calculating vapor pressures the data were edited. Editing consisted largely of filling in obvious values of missing data, such as those resulting from brief service visits, and interpolating radiometer data during rainfall when the exposed sensor was wet. Adjustments for frozen wet bulbs were made when required.

The four psychrometers were changed frequently to avoid errors caused by dust, pollen, and corrosion of the thermojunctions. Although carefully constructed, the thermocouple-wick-reservoir assemblies could not be perfectly duplicated, and on several occasions a small adjustment (never greater than 0.25°C) was made to one or more of the temperature values based on readings made with the Assman-type psychrometer.

Rain accumulated in the gage between service visits (made about twice a week) was distributed according to time and intensity by observing its effect upon the exposed flat plate of the radiometer. The accumulation of water in the rain gage was subject to evaporation and, in summer, when more than 2 days had passed between a rainstorm and its measurement, 3 percent per day was added to the catch.

All data needed for analyses were then punched on cards; only one card for each 4-h period was necessary.

DATA ANALYSES

Net advection by the ambient air (and water) was assumed to be negligible. Change in heat stored in the green vegetation was estimated and also found to be negligible. The net flux of heat by the mass of evaporated water was also considered slight. Thus the heat balance at the surface could be written:

$$L(ET) = N - H - Q - C + P \tag{1}$$

where

ET is evapotranspiration (centimeter per minute),

L is the latent heat of evaporation (calorie per cubic centimeter),

N is the net radiation (calorie per square centimeter minute),

H is the heat flow at the 50-cm depth in soil (calorie per square centimeter minute),

Q is the change-in-heat storage in the top 50-cm soil layer (calorie per square centimeter minute),

C is the convected, or vertically transported, sensible heat (calorie per square centimeter minute), and

P is the heat content of the mass of fallen rain (calorie per square centimeter minute).

The latent heat, L, was calculated as a function of temperature because of the wide range of measured values during the experiment. The 1-m wet-bulb temperature was preferred, but if it was missing, the 2-m value was used, and if that was missing, the 4-m wet-bulb temperature was accepted. If all three were missing, the 1-m air temperature or 2-m air temperature was substituted when required.

The net radiation, N, is the net total-spectrum thermal radiation between Earth and sky and is the largest source of variation for ET when water is available. N was measured directly.

The vertical heat flow, H, measured with the two heat-flow plates at a depth of 50 cm, may be either up (negative) or down (positive). The value of H was usually only a few percent of N on a daily basis, with values ranging between -0.013 and +0.011 cal/(cm^2 min) during the observation period. In this study, downward heat flow was considered as energy not immediately available for evapotranspiration.

The value of Q, the change-in-heat stored in the uppermost 50-cm soil layer above the heat flow plates was the third largest source of ET variation. The method of computation adopted for Q required computing the average temperature of the soil layer at the end and at the beginning of each 4-h period, and then subtracting. The difference of the average temperatures multiplied by the average heat capacity and then divided by the period length of 240 minutes gave an average flux value for the period. Because of a lack of sufficient measurements of temperatures closely spaced in depth, average temperatures at the beginning and end of each 4-h period had to be estimated using classical Fourier synthesis (Carson, 1963). A solution of the differential equation of one-dimensional heat flow into a semi-infinite solid is:

$$T_s(z,k) = \overline{T}_s(z) + \sum_n A_n \exp(-z\sqrt{n\pi/\alpha p})\sin(2\pi nk/p - z\sqrt{n\pi/\alpha p} + \phi_n), \qquad (2)$$

where T_s is soil temperature; k is time; z is depth; α is the thermal diffusivity; and the period considered, p, is one day. Taking the boundary condition to be the nominal 2-cm depth temperature value, four amplitude coefficients A_n and four phase angles ϕ_n were evaluated on 30 days, using 24 hourly values each day. The days chosen had a wide range of soil moisture and temperature values. When computations were made only limited computer facilities were available, so that amplitude coefficients and phase angles could not be computed for each of the 363 days. Simplifications, based on the diurnal range of temperature, soil moisture conditions, and the day of the year, proved adequate for estimating the first 4 harmonic terms of equation 2 (Leppanen, 1980, p. 12-14).

The variation of the thermal diffusivity, α, with soil moisture was calculated after integrating equation 2 with respect to depth from $z = 0$ to $z = 48$, using selected 2-h periods just before sunrise (Leppanen, 1980, p. 14-16).

The change-in-heat-storage, Q, was then calculable as

$$Q = C_p \Delta\overline{T}_s$$

where $\Delta\overline{T}_s$ is the change in average temperature of the 50-cm soil layer over a 4-h period and C_p (in cal/(cm^2 min °C)) is a heat capacity coefficient which varies with soil moisture.

Initially, the convected heat, C, was not evaluated directly. It entered evapotranspiration computations when the energy balance was expressed in Bowen ratio form, in which the Bowen ratio is defined as the ratio of vertically transported sensible heat to vertically transported latent heat.

Thermal mass added by rain, P, was estimated by using wet-bulb temperature as an estimate of rain temperature. Rain temperatures below 1.5°C were not accepted.

Equation 1 written in Bowen ratio form is

$$ET = \frac{N - H - Q + P}{L(1 + BR)} \quad , \tag{3}$$

with

$$BR = \frac{C}{L(ET)} = m \frac{K_T \text{ grad } T}{K_e \text{ grad } e} = m \frac{\partial T/\partial z}{\partial e/\partial z} \quad , \tag{4}$$

where K_T and K_e are eddy transfer coefficients assumed equal, T is air temperature, e is vapor pressure, and z is height. The coefficient m was assumed constant and with T in degrees Celsius and e in millibars equaled 0.617.

Considerable difficulty was encountered in evaluating Bowen ratios because of imprecision of data and the numerical techniques used. The best method found was to use a linear model of the variation of temperature and vapor pressure with the logarithm of adjusted elevation (Leppanen, 1980, p. 16-17). The adjustment to elevation, D, was somewhat analogous to computing a displacement height. The adjustment was computed by varying the parameter value, D, from 0 to 150 cm by 10-cm increments and summing the squared errors-of-fitting to the measured profiles. The smallest error-sum would indicate the best displacement height. The values of D were chosen to cover the range of vegetation height during each of five seasonal periods: first summer, fall, winter, spring, and second summer. The fit of vapor and temperature profiles was almost identical. Surprisingly, the seasonal variation in the adjustment height did not fluctuate greatly; however, values could not be determined precisely but only within a 20-cm range. All seasonal ranges overlapped. Because of this overlap and because plots of error-sum against adjustment height showed a distinct flattening over 30-cm regions of the adjustment height, one value equal to 57 cm was chosen to represent all seasons. (All arithmetic was done in double-precision using modern computer facilities.) Bowen ratios and preliminary evapotranspiration values were then computed for each 4-h period.

Many evapotranspiration values were missing and many were obviously incorrect. Logarithmic profiles were not computed if data from more than one of the four elevations were missing. When the Bowen ratio was near -1, small measurement errors in the numerator of equation 3 were greatly magnified. If the numerator of equation 4 was small when the denominator was very small, *ET* values could vary widely and inconsistently. To eliminate these, and other problems, a supplemental method of computation was adopted.

The supplemental method had been used by other investigators (Slatyer and McIlroy, 1961) and follows directly from equation 3 and the psychrometric equation when the Bowen ratio is computed using a two-elevation difference quotient (divided differences).

Thus

$$BR = m \frac{T_{ai} - T_{aj}}{e_i - e_j} = m \frac{\Delta T_a}{\Delta e}$$

where the subscripts i and j refer to different elevations above the ground surface, and T_a is the air temperature.

The psychrometric equation is

$$e = e_s\,(T_w) - k_1\,b\,(T_a - T_w)(1 + k_2 T_w)$$

where e is vapor pressure, e_s is saturation vapor-pressure at temperature T, T_w is the wet-bulb temperature and T_a is the dry-bulb temperature, b is barometric pressure and k_1 and k_2 are constants. The constant k_2 is small. Substituting the psychrometric equation (with $k_2 = 0$) into the difference quotient form of BR, the second factor in the denominator of equation 3 is

$$1 + BR = \frac{s\Delta T_w - \gamma\Delta T_a + \gamma\Delta T_w + \gamma\Delta T_a}{s\Delta T_w - \gamma\Delta T_a + \gamma\Delta T_w}$$

where s is the approximate slope of the saturation vapor pressure curve with temperature between the wet-bulb temperatures T_{wi} and T_{wj}, and γ is the local psychrometric constant, $k_1 b$. The coefficient m is assumed to equal γ numerically.

Inverting the expression for $1 + BR$ and simplifying yields

$$L(ET) = (N - H - Q + P)\left(1 - \frac{\gamma}{s + \gamma} \cdot \frac{\Delta T_a}{\Delta T_w}\right) \qquad (5)$$

which was used as the supplemental equation for calculating ET. Comparison of equation 1 with equation 5 shows that the effect of the second factor of equation 5 is to separate a portion of (N - H - Q + P) into a heat flux representing the convection, C.

Before applying equation 5 to the unsatisfactory 4-h periods, two preliminary tests were applied: if the calculated vapor gradient was very small, ET was set to zero; if a very large evaporating vapor gradient was calculated, but condensation resulted, ET was set to zero. In computer runs, the former test applied nine times, but the latter only twice. Additionally, on one very foggy winter day the numerator of equation 3 remained negative for most of the day; ET was also set to zero.

Equation 5 was applied to 4-h period data when the following situations occurred: BR near minus one ($-1.54 < BR < -0.44$); very large negative BR in daytime ($BR < -4$); and BR missing. In using equation 5 the measurement elevations chosen were the 2- and 4-m heights. It would have been theoretically more appropriate to use the 1- and 2-m heights, but preliminary investigation had shown the 1-m temperature data to be anomalously affected when taken below the vegetation tops, resulting in atypical difference quotients. However, if 2-m data were missing, 1-m data were used. Also, if the 4-m data were missing, 8-m data were used.

Although improving data yield considerably, use of equation 5 was not fully satisfactory, largely because of numerical imprecision in temperature data (and also because of experimental errors). Very small wet-bulb differences (temperatures were tabulated to the closest 0.1°C) or occasions with no difference resulted in unusable ET data. Such 4-h period data were declared to be missing. A few other anomalous situations occurred and their corresponding *ET* data were also marked as missing.

After applying equation 5 to 4-h periods during which the station was operating, a considerable number of *ET* values remained to be evaluated. Of these, many were missing because of dry wet-bulbs or other vapor pressure measurement difficulties such as open aspirator pipe joints. Equation 1 could be applied if convection estimates were made, because air temperature data were often available when wet-bulb data were missing or unusable in equation 3 or equation 5.

The 363-day observation period data were divided into six seasons: first summer, monsoon, fall, winter, spring rains, and second summer. Within each season, data were grouped according to the six daily 4-h periods, so that 36 sets were available for analysis. This division of data according to surface conditions and time-of-day was made because no wind data were gathered, precluding analysis using a stability parameter.

The linear regression of convection on temperature slope was computed for each set of data, and outlying data removed using criteria based on the standard deviation. The 36 lines were then recomputed, constrained to pass through the origin. Figure 4 is an example of such a fit for the period 1600-2000 during the first summer. Convection data departing more than 2.5 standard deviations from the first regression have been removed (two samples). Using the 36 convection equations, convection was estimated for missing 4-h periods for which temperature slope data were available. *ET* was then computed using equation 1.

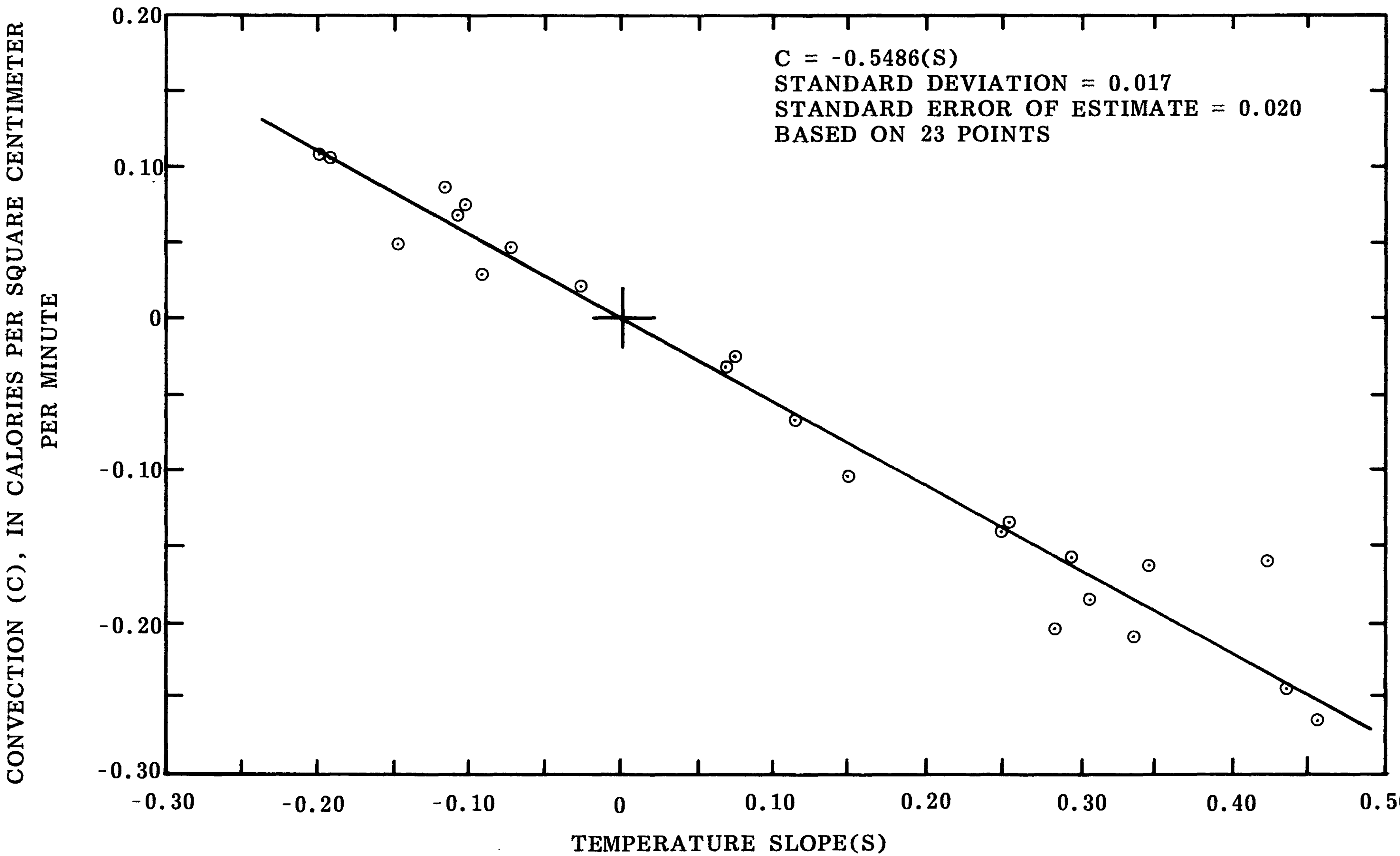

Figure 4.--Convected heat variation with temperature slope, 1600-2000, first summer.

Of the possible 2,178 4-h periods in the 363-day observation period, 1,802 were now usable, leaving 376 still missing. Next, another computation of daily evapotranspiration revealed that 87 days (24 percent) did not have six complete 4-h periods, or were completely missing.

A NWS Class-A meteorological observation station, with evaporation pan, was operated at Coolidge Dam (San Carlos Reservoir), about 32 km from the evapotranspiration measurement site. Daily values of the maximum and minimum air temperatures, pan evaporation, wind movement at the pan, and precipitation were available to estimate daily evapotranspiration for the 87 missing days. These NWS data were added to the *ET* data file.

Pan coefficients were calculated (daily *ET* divided by daily pan evaporation) and days having one of the few negative coefficients removed from the file. Using the same six seasons as were used in the convection analyses, average pan coefficients were computed. On the basis of seasonal standard deviations, the extreme 10 percent of pan coefficient values were noted, and days having one of these were removed from the data file. Plots of pan coefficients against wind movement showed no correlation; errors due to splashout and heavy rains had apparently been removed by the editing procedure.

Daily evapotranspiration was then estimated with a linear statistical model which used as independent variables the daily pan evaporation, daily wind movement, median air temperature, and another variable called vapor deficit. Such a vapor-deficit variable had been previously found to be useful (Leppanen, 1980, p. 20-21) but because no humidity data were gathered at the NWS station, a somewhat questionable assumption had to be made in order to estimate the true vapor deficit. This was that the daily minimum air temperature (recorded at 0540 mean solar time by the station operator) was near the saturation vapor-pressure temperature, and resulted in an expression for the vapor deficit

$$V = (1/2)(T_{\text{max}} - T_{\text{min}})(s + 0.611)$$

where T_{max} and T_{min} are the daily NWS maximum and minimum air temperatures (in degrees Celsius) and s is the slope of the saturation vapor-pressure curve against temperature calculated at the temperature given by $(1/4)(T_{\text{max}} + 3T_{\text{min}})$.

The coefficients of the four-variable model were calculated for each of the six seasons with a statistical procedure which chose among the independent variables in the order each variable contributed most to the coefficient of multiple correlation. In five of the six seasons (fall was the exception) the pan evaporation was the most important variable. The vapor deficit and the wind movement were each the secondmost significant in three of the six seasons. Median air temperature was a poor estimator, except in the fall when it was best (and vapor deficit the worst). The four-variable linear model, overall, was highly significant; applying the F-test, the first four seasons had probabilities greater than 0.0001. The spring-rains season had probability greater than 0.006, but the second summer had, for some unknown and uninvestigated reason, a probability greater than 0.12, by far the worst. The second-summer coefficient of multiple correlation was also poor, 0.44. The coefficients for other seasons averaged 0.75, with the first summer being the best, 0.94. The positive intercept constants in the six models were all less than 1.33 mm *ET*, except for the fall, which had a constant of -2.01 mm of water.

Using the six models, *ET* was estimated for incomplete and missing days. This completed the 363-day record.

During the course of the analyses, numerical quality ratings were assigned to each 4-h period according to criteria determined by which arithmetic procedures had been used in arriving at the *ET* value. This quality-rating resulted in 15 gradations of 4-h period data. The number 0 represented the case when no estimates were made. Quality 1 was used to describe a 4-h period with a very small vapor gradient (less than 0.0001 millibars/ln $(z - D)$). Twelve of the other 13 numbers represented cases when equation 5 was used or when empirical convection estimates were made. The remaining quality number described a few 4-h periods with heavy fog or drizzle.

To rate a daily *ET* value, the number of 4-h periods with ratings other than 0 or 1 was counted. This procedure resulted in daily quality-ratings ranging from 0 (all measured data) to 3 (three periods with 4-h ratings other than 0 or 1). The number 8 was used to describe days with four nondaytime 4-h periods rated greater than 1. The number 9 was used when the estimating equation using NWS data was applied.

RESULTS AND DISCUSSION

Table 1 lists the daily evapotranspiration estimates, the loss (defined as evapotranspiration less rainfall), and the quality rating for each of the 363 days of the study. The loss listing, however, does not include the 30 mm of rain inferred to have fallen on March 29, 1970, as discussed in the section on water available for evapotranspiration. Figure 5, a plot of the daily course of evapotranspiration and rainfall, shows the inferred, unmeasured, 30 mm of rain on March 29, 1970 as a dotted line.

The 363-day total evapotranspiration was 983.8 mm, including questionable values of indicated condensation of 0.92 mm on November 16, 1969, a day with heavy rain, and condensation of 0.37 mm on December 28, 1969, another rainy day. Rainfall was 332.2 mm, including the unmeasured 30 mm. These data indicate that nearly three times the local rainfall was used in transpiration, interception evaporation, and soil evaporation. Runoff could not have contributed 652 mm of soil moisture without being prominently noticeable in the soil moisture record, or remarked upon by observers visiting the station. The rainfall quantity is reasonable, and if the evapotranspiration record is at all reasonable, the most likely conclusion is that large quantities of water had been transferred from the capillary fringe or from the 2-m deep water table.

To interpret further the moisture-transfer phenomena, several periods in which infiltration or percolation was not too great a complicating factor were investigated. Five suitable 1- and 2-week periods were found in which cumulative soil-moisture depletion with depth could be compared with energy budget evapotranspiration, and which

Table 1.--Daily evapotranspiration (*ET*) and loss, in millimeters

DATE	QUAL	ET	LOSS	DATE	QUAL	ET	LOSS
6-19-69	9	4.91	4.91	8- 4-69	2	7.92	7.92
6-20-69	2	5.35	5.35	8- 5-69	9	7.37	0.97
6-21-69	2	5.31	5.31	8- 6-69	9	6.84	4.34
6-22-69	2	4.92	4.92	8- 7-69	9	6.77	5.47
6-23-69	1	4.09	4.09	8- 8-69	8	8.75	8.76
6-24-69	2	4.81	4.81	8- 9-69	9	7.59	7.59
6-25-69	2	3.68	3.68	8-10-69	9	6.30	5.30
6-26-69	0	3.79	3.79	8-11-69	9	5.95	5.46
6-27-69	1	4.47	4.47	8-12-69	2	4.87	2.75
6-28-69	3	5.54	5.54	8-13-69	3	6.39	2.78
6-29-69	1	4.83	4.83	8-14-69	1	7.65	5.12
6-30-69	3	5.20	5.20	8-15-69	9	7.46	7.46
7- 1-69	3	4.75	2.95	8-16-69	3	8.10	8.10
7- 2-69	8	5.83	5.83	8-17-69	9	6.55	6.55
7- 3-69	8	6.13	6.13	8-18-69	9	5.75	5.75
7- 4-69	3	5.51	5.51	8-19-69	3	6.15	5.92
7- 5-69	1	5.37	5.37	8-20-69	8	7.67	7.67
7- 6-69	8	5.55	5.55	8-21-69	8	7.61	7.31
7- 7-69	9	4.77	4.77	8-22-69	3	7.21	7.21
7- 8-69	1	4.33	4.33	8-23-69	3	7.00	6.88
7- 9-69	1	2.51	2.51	8-24-69	8	5.20	4.97
7-10-69	1	4.65	4.65	8-25-69	3	4.83	-1.57
7-11-69	2	2.77	2.77	8-26-69	8	6.79	6.79
7-12-69	1	2.28	2.28	8-27-69	8	6.09	6.09
7-13-69	1	4.06	4.06	8-28-69	3	5.44	3.93
7-14-69	2	3.89	3.89	8-29-69	1	3.12	1.98
7-15-69	1	3.85	3.85	8-30-69	2	5.58	5.58
7-16-69	2	5.28	-1.62	8-31-69	1	4.68	4.68
7-17-69	1	5.45	5.45	9- 1-69	1	3.73	3.29
7-18-69	2	5.33	-9.37	9- 2-69	1	4.27	4.27
7-19-69	3	4.27	-0.26	9- 3-69	3	3.95	3.95
7-20-69	9	5.74	3.94	9- 4-69	3	2.83	2.83
7-21-69	9	7.33	7.03	9- 5-69	2	4.20	4.20
7-22-69	9	6.07	5.77	9- 6-69	3	4.15	4.15
7-23-69	2	5.70	5.70	9- 7-69	3	3.23	2.77
7-24-69	8	9.17	9.17	9- 8-69	2	3.65	3.65
7-25-69	9	6.15	6.15	9- 9-69	2	2.57	2.57
7-26-69	9	5.50	5.50	9-10-69	3	3.55	3.55
7-27-69	9	5.52	4.22	9-11-69	8	2.65	-12.41
7-28-69	3	6.08	6.08	9-12-69	2	2.78	-7.37
7-29-69	9	6.51	6.51	9-13-69	2	3.05	2.13
7-30-69	9	8.25	8.25	9-14-69	3	4.33	4.33
7-31-69	8	7.13	5.83	9-15-69	1	4.13	3.44
8- 1-69	3	8.39	8.39	9-16-69	2	5.32	5.32
8- 2-69	9	3.25	3.25	9-17-69	8	7.97	7.97
8- 3-69	3	7.00	5.00	9-18-69	2	6.00	5.00

DATE	QUAL	ET	LOSS	DATE	QUAL	ET	LOSS
9-19-69	2	5.88	5.88	11- 4-69	0	0.75	0.75
9-20-69	8	6.23	6.23	11- 5-69	1	1.67	1.67
9-21-69	8	5.09	5.09	11- 6-69	8	1.77	1.77
9-22-69	3	5.58	5.58	11- 7-69	8	2.10	2.10
9-23-69	2	5.75	5.75	11- 8-69	0	0.72	0.72
9-24-69	3	5.33	5.33	11- 9-69	1	-0.43	-9.34
9-25-69	3	5.93	5.93	11-10-69	2	-0.06	-2.25
9-26-69	3	5.08	5.08	11-11-69	0	0.36	0.36
9-27-69	2	4.71	4.71	11-12-69	0	0.71	0.71
9-28-69	2	4.39	4.39	11-13-69	1	0.26	0.26
9-29-69	2	4.74	4.74	11-14-69	1	0.27	0.27
9-30-69	3	4.69	4.69	11-15-69	2	0.94	-11.19
10- 1-69	8	4.04	4.04	11-16-69	3	-0.92	-30.74
10- 2-69	2	3.45	3.45	11-17-69	2	1.73	1.73
10- 3-69	2	3.72	3.72	11-18-69	0	1.69	1.69
10- 4-69	9	3.14	3.14	11-19-69	3	1.44	1.44
10- 5-69	9	1.62	1.62	11-20-69	9	1.15	1.15
10- 6-69	9	2.68	2.68	11-21-69	9	0.57	0.57
10- 7-69	9	2.54	2.54	11-22-69	1	0.63	0.63
10- 8-69	3	3.59	3.59	11-23-69	0	0.37	0.37
10- 9-69	2	3.18	3.18	11-24-69	0	0.67	0.67
10-10-69	1	2.97	2.97	11-25-69	0	0.58	0.58
10-11-69	2	1.55	1.55	11-26-69	0	0.94	0.94
10-12-69	0	0.78	0.78	11-27-69	1	0.69	0.69
10-13-69	1	1.24	1.24	11-28-69	3	0.48	-1.09
10-14-69	1	1.67	1.67	11-29-69	0	0.20	0.20
10-15-69	0	1.21	1.21	11-30-69	1	0.89	0.89
10-16-69	1	0.88	0.88	12- 1-69	0	0.94	0.94
10-17-69	1	1.25	1.25	12- 2-69	2	0.12	0.12
10-18-69	1	1.33	1.33	12- 3-69	8	-0.14	-9.87
10-19-69	0	1.41	1.41	12- 4-69	9	0.23	-5.63
10-20-69	9	1.45	-2.35	12- 5-69	1	0.64	0.64
10-21-69	1	1.57	-1.64	12- 6-69	0	0.38	0.38
10-22-69	0	0.31	-2.30	12- 7-69	2	0.68	0.68
10-23-69	0	0.91	0.91	12- 8-69	0	0.75	0.75
10-24-69	1	1.64	1.64	12- 9-69	2	0.17	-1.28
10-25-69	1	1.51	1.51	12-10-69	0	0.83	0.83
10-26-69	1	2.13	2.13	12-11-69	0	1.36	1.36
10-27-69	0	1.31	1.31	12-12-69	0	0.12	0.12
10-28-69	0	1.71	1.71	12-13-69	0	0.28	0.28
10-29-69	0	1.29	1.29	12-14-69	0	-0.03	-0.03
10-30-69	0	1.70	1.70	12-15-69	0	0.19	0.19
10-31-69	0	1.00	1.00	12-16-69	0	-0.07	-0.07
11- 1-69	3	2.00	2.00	12-17-69	1	0.39	0.39
11- 2-69	0	0.52	0.52	12-18-69	0	0.65	0.65
11- 3-69	0	1.59	1.59	12-19-69	0	0.39	0.39

Table 1.--Daily evapotranspiration (*ET*) and loss, in millimeters

DATE	QUAL	ET	LOSS	DATE	QUAL	ET	LOSS	DATE	QUAL	ET	LOSS	DATE	QUAL	ET	LOSS
12-20-69	0	0.55	0.55	2- 4-70	9	0.58	0.58	3-22-70	2	0.96	0.95	5- 7-70	9	2.96	2.96
12-21-69	0	0.74	0.74	2- 5-70	9	1.23	1.23	3-23-70	9	2.05	2.05	5- 8-70	1	2.29	2.29
12-22-69	0	1.36	1.36	2- 6-70	9	0.97	0.97	3-24-70	9	2.51	2.51	5- 9-70	2	2.22	2.22
12-23-69	0	0.84	0.84	2- 7-70	9	1.21	1.21	3-25-70	9	2.06	1.25	5-10-70	1	1.95	1.95
12-24-69	0	0.87	0.87	2- 8-70	9	1.28	1.28	3-26-70	9	2.97	2.97	5-11-70	1	2.73	2.73
12-25-69	0	0.57	0.57	2- 9-70	9	1.15	1.15	3-27-70	9	1.05	1.05	5-12-70	2	3.46	3.46
12-26-69	0	0.71	0.71	2-10-70	9	0.90	0.90	3-28-70	9	1.96	1.95	5-13-70	1	3.98	3.98
12-27-69	2	0.46	-5.56	2-11-70	9	0.33	-2.17	3-29-70	9	1.82	1.82	5-14-70	2	4.93	4.93
12-28-69	3	-0.37	-6.83	2-12-70	9	0.71	-0.29	3-30-70	9	1.81	1.81	5-15-70	1	2.13	2.13
12-29-69	1	0.71	-2.39	2-13-70	9	0.89	0.89	3-31-70	0	0.92	-3.24	5-16-70	2	4.04	4.04
12-30-69	1	0.35	0.35	2-14-70	0	1.49	0.85	4- 1-70	1	1.14	1.14	5-17-70	2	3.78	3.78
12-31-69	1	0.71	0.71	2-15-70	1	1.03	1.03	4- 2-70	1	2.06	2.05	5-18-70	1	2.40	2.40
1- 1-70	0	0.84	0.84	2-16-70	2	1.96	1.96	4- 3-70	2	2.13	2.13	5-19-70	1	4.52	4.52
1- 2-70	1	1.67	1.67	2-17-70	2	0.90	0.90	4- 4-70	2	1.24	1.24	5-20-70	2	4.44	4.44
1- 3-70	2	1.11	1.11	2-18-70	1	1.97	1.97	4- 5-70	2	3.16	3.15	5-21-70	1	5.12	5.12
1- 4-70	2	1.80	1.80	2-19-70	3	0.71	0.71	4- 6-70	8	4.09	4.09	5-22-70	9	3.49	3.49
1- 5-70	0	0.67	0.67	2-20-70	2	1.05	-0.80	4- 7-70	2	2.32	2.32	5-23-70	9	3.33	3.33
1- 6-70	0	0.58	0.58	2-21-70	2	1.41	0.23	4- 8-70	1	2.41	2.41	5-24-70	9	3.37	3.37
1- 7-70	1	0.26	0.26	2-22-70	1	1.32	1.32	4- 9-70	2	1.45	1.45	5-25-70	9	2.38	1.58
1- 8-70	0	0.96	0.96	2-23-70	1	1.10	0.80	4-10-70	3	1.04	1.04	5-26-70	9	2.69	2.69
1- 9-70	2	0.60	0.10	2-24-70	1	2.25	2.25	4-11-70	3	3.69	3.69	5-27-70	9	2.82	2.82
1-10-70	3	0.22	0.22	2-25-70	1	2.83	1.23	4-12-70	1	2.60	2.60	5-28-70	2	4.76	4.76
1-11-70	9	0.51	0.51	2-26-70	1	1.69	0.09	4-13-70	1	2.31	2.31	5-29-70	1	2.11	2.11
1-12-70	9	0.76	0.76	2-27-70	1	1.35	1.35	4-14-70	2	2.68	2.68	5-30-70	2	4.99	4.99
1-13-70	9	0.73	0.73	2-28-70	2	1.93	1.93	4-15-70	2	1.94	1.94	5-31-70	2	4.57	4.57
1-14-70	9	0.55	0.55	3- 1-70	3	2.69	-19.62	4-16-70	2	3.70	3.70	6- 1-70	2	2.68	2.68
1-15-70	9	0.73	0.73	3- 2-70	2	0.35	-26.73	4-17-70	3	1.44	-1.69	6- 2-70	1	2.43	2.43
1-16-70	9	0.80	0.30	3- 3-70	9	0.50	-8.47	4-18-70	3	1.14	-2.25	6- 3-70	1	2.53	2.53
1-17-70	9	0.58	-0.42	3- 4-70	9	0.52	-21.88	4-19-70	1	3.60	3.60	6- 4-70	2	1.19	1.19
1-18-70	9	0.83	0.83	3- 5-70	1	0.51	-1.99	4-20-70	3	2.17	2.17	6- 5-70	2	1.54	1.54
1-19-70	9	0.75	0.75	3- 6-70	1	1.99	1.99	4-21-70	2	3.11	3.11	6- 6-70	1	3.48	3.48
1-20-70	9	0.83	0.83	3- 7-70	0	1.31	1.31	4-22-70	1	2.25	2.25	6- 7-70	9	2.92	2.92
1-21-70	9	0.64	0.64	3- 8-70	0	0.75	0.76	4-23-70	2	3.35	3.35	6- 8-70	9	3.36	3.36
1-22-70	9	0.79	0.79	3- 9-70	0	1.69	1.69	4-24-70	2	1.88	1.88	6- 9-70	9	2.98	2.98
1-23-70	9	0.64	0.64	3-10-70	1	0.49	-3.18	4-25-70	2	3.30	3.30	6-10-70	9	3.09	3.09
1-24-70	9	0.88	0.88	3-11-70	2	0.12	-0.81	4-26-70	2	3.18	3.18	6-11-70	0	1.93	1.93
1-25-70	9	0.64	0.64	3-12-70	0	0.70	0.20	4-27-70	2	2.96	2.95	6-12-70	1	3.26	3.26
1-26-70	9	0.98	0.98	3-13-70	1	1.67	1.67	4-28-70	1	1.71	1.71	6-13-70	1	3.41	3.41
1-27-70	9	1.23	1.23	3-14-70	2	2.08	2.08	4-29-70	2	2.23	2.23	6-14-70	1	2.46	2.46
1-28-70	9	1.53	1.53	3-15-70	1	1.65	1.65	4-30-70	2	1.11	1.11	6-15-70	1	3.85	3.85
1-29-70	9	1.08	1.08	3-16-70	1	2.50	2.50	5- 1-70	0	3.13	3.13	6-16-70	1	1.86	1.86
1-30-70	9	1.14	1.14	3-17-70	1	1.67	1.67	5- 2-70	9	2.94	2.94				
1-31-70	9	1.51	1.51	3-18-70	3	1.65	1.65	5- 3-70	9	2.38	2.38				
2- 1-70	9	1.06	1.05	3-19-70	2	1.75	1.75	5- 4-70	9	3.53	3.53				
2- 2-70	9	0.95	0.95	3-20-70	2	2.65	2.66	5- 5-70	9	2.73	2.73				
2- 3-70	9	1.04	1.04	3-21-70	2	1.14	1.14	5- 6-70	9	2.92	2.92				

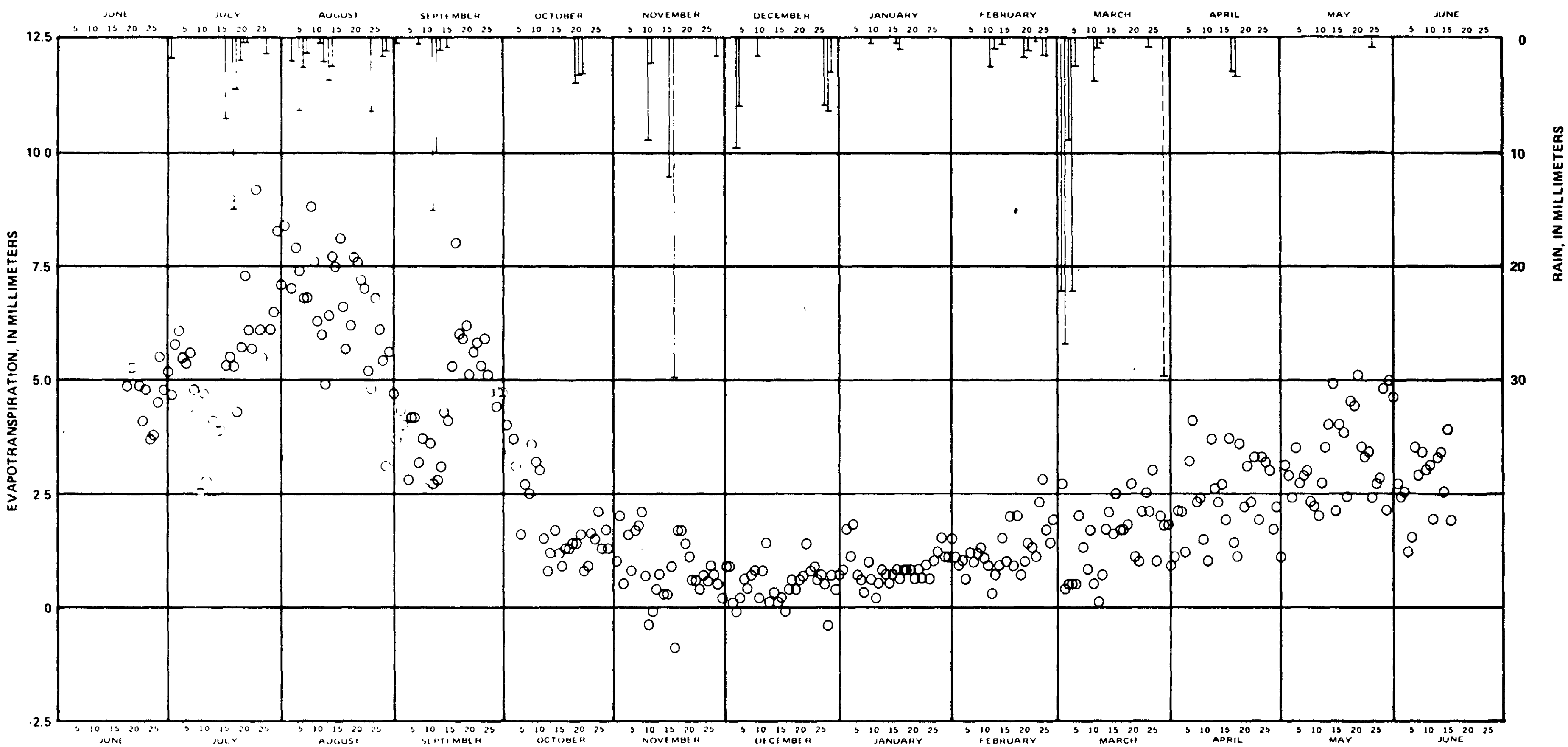

Figure 5.--Daily evapotranspiration and precipitation, 1969 and 1970.

did not contain too much interpolated energy budget data. Data from these periods are plotted in figure 6. Details are discussed below, but it should be borne in mind that data from only one soil moisture measurement location cannot be considered adequate to define an accurate water-budget control. Recall also that depth to water was estimated from the annual course of soil-moisture readings at the various depths.

Of the five chosen periods, complications were greatest in the period January 2 to January 9, 1970. A small amount of rain (0.5 mm) fell on January 9, just before the soil moisture profile observation was made. This sprinkle was ignored. Rain, totaling 15.6 mm, had fallen on December 27, 28, and 29, 1969 leaving only 4 days for any infiltration to stabilize in the soil moisture profile. However, because 23 days without significant rainfall had preceded the 3 rainy days in December, data from January 2, 1970 were deemed usable. The vegetation was dormant so only soil evaporation occurred, apparently stabilizing at a rate of 1.0 mm/d above 100 cm depth, as shown in figure 6. Energy budget evapotranspiration for the period was 0.95 mm/d, plotted as the horizontal dashed line intersecting the depletion curve (fig. 6). The short vertical bar crossing the depletion with depth curve is located 50 cm above the shallowest estimated water-table depth (223 cm) during the 7.05-day period. (The other depletion curves in figure 6 are similarly marked. Curves for the periods April 24 - May 1, 1970, May 8 - May 22, 1970, and May 28 - June 12, 1970, indicate depletion

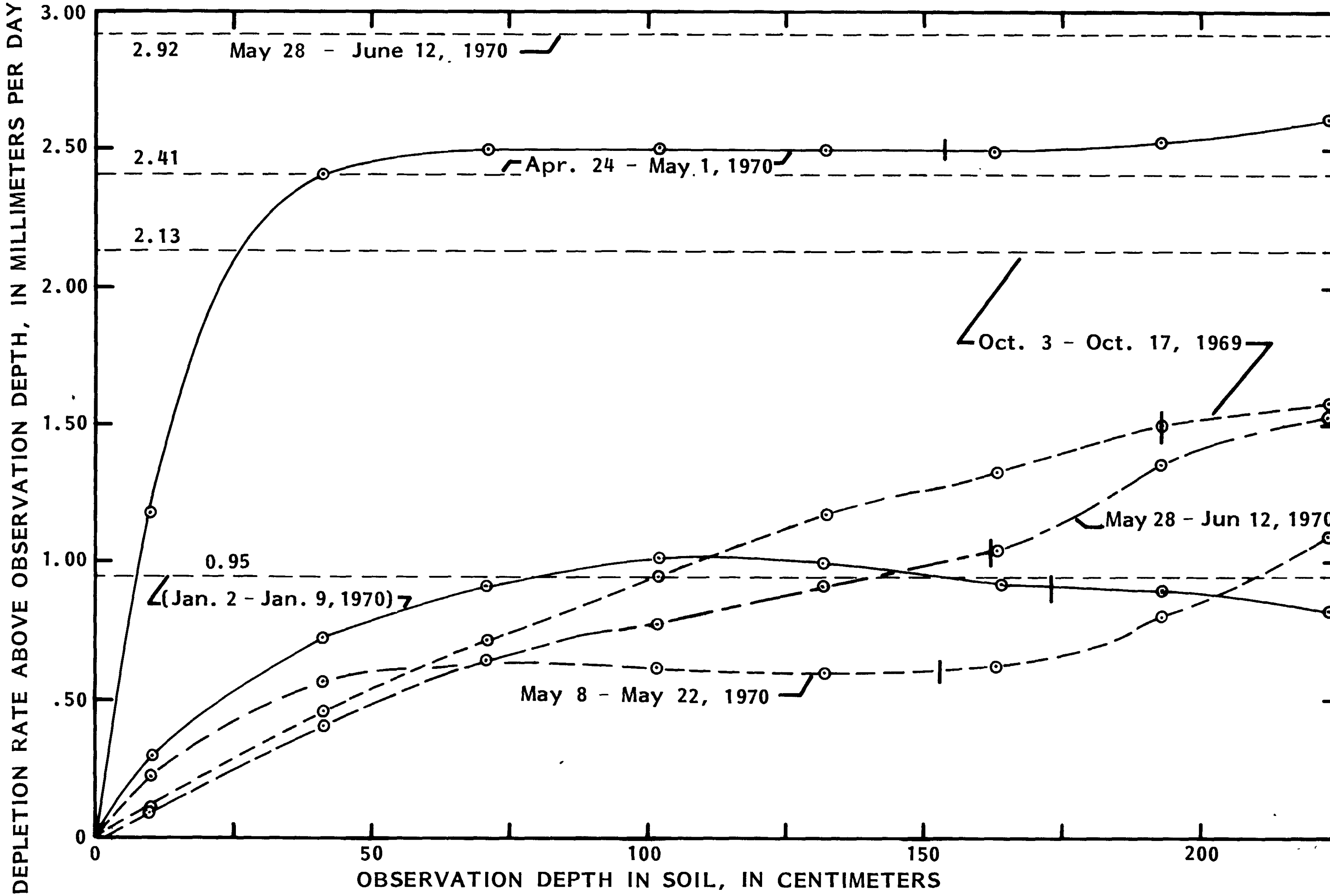

Figure 6. Cumulative soil moisture depletion rate with depth for selected periods. Short vertical bars across curves indicate depths below which capillary fringe effects may become significant. The four horizontal dashed lines represent evapotranspiration calculated from energy budget data. Energy budget evapotranspiration for the period May 8 - May 22, 1970 (3.46 mm/d) is not shown.

below the estimated depth of the water table. This may be due to the nature of the neutron-scattering meter used to measure water content. Neutron energy attenuation occurs in a pseudospherical region which may include some nonsaturated soil above the water table.)

The depletion-with-depth curve for a week (April 24 to May 1, 1970) almost 4 months later reflected the effects of spring rains in March. Depletion stabilized at about 70 cm depth, although some depletion of the capillary fringe apparently occurred above the nearly constant water table at 204 cm depth. The panicgrass, which is a hot weather plant, had not yet grown appreciably, but other, much more scattered vegetation had. No rain had fallen in the 6 days preceding April 24: a total of 6.5 mm had fallen in the next 2 antecedent days, and there had been no rain in the 17 days before these two. Energy budget evapotranspiration of 2.41 mm/d matched the depletion curve fairly well, as is seen in figure 6.

The other three cumulative depletion-with-depth curves differed considerably from the two discussed above. Energy budget evapotranspiration was much greater than the soil moisture depletion, suggesting that moisture was transferred from the capillary fringe and water table. Two of the three corresponding energy budget evapotranspiration rates are shown in figure 6; the other rate was 3.46 mm/d (not plotted) for the period May 8 to May 22, 1970. This 2-week mid-May period was preceded by 20 rainless days. Apparently, there was no net contribution to evapotranspiration from soil moisture between the 50- to 150-cm depths (see fig. 6). The indicated soil-moisture depletion of 0.6 mm/d is not enough to sustain the grass that was now growing vigorously, and is less than the quantity expected to be evaporated from bare soil with a 2-m deep water table (Ripple and others, 1972). The depth to the water table increased slightly from 203 cm to 207 cm during the interval May 8 to May 22, 1970.

Three days before the 2-week period beginning May 28, 1970, 0.8 mm of rain fell. Such a small amount would have little effect on the soil moisture profile, especially since no rain had fallen for 40 days, otherwise. The depletion curve (May 28 to June 12, 1970) maintains a positive slope with depth throughout its range, indicating that more and more soil moisture is depleted with increasing depth. However, the maximum net depletion rate of about 1.5 mm/d would barely be enough to sustain panicgrass. Soil moisture content at the 102-cm depth was 6.81 percent by volume (about 4.7 percent by weight) at the beginning of the period and soil moisture at the 132-cm depth was 7.57 percent by volume (about 5.3 percent by weight). Surprisingly, these very low moisture contents were further decreased by 0.84 percent and 0.61 percent, respectively, by the end of the period. Energy budget evapotranspiration averaged 2.92 mm/d during this June period and the water table fell from 212 cm to 230 cm.

The period from October 3 to October 17, 1969, was preceded by 18 dry days during which evapotranspiration declined rapidly with the approach of fall. After the rains of the monsoon season, ending in mid-September, soil moisture above the capillary fringe was probably adequate for growth, but the maximum depletion rate was only

1.6 mm/d. Even though the panicgrass was in its first growing season, this would be barely enough to sustain turgor in dense vegetation over 1 m tall (fig. 3). Average calculated evapotranspiration was 2.13 mm/d and the water table rose from 249 cm to 243 cm during this period.

The five depletion curves shown in figure 6 suggest that either the grass roots extended deeper than anticipated, or large amounts of vapor were transferred from ground water, or both. Because of the desert climate at the site and the relatively shallow water table, large temperature and vapor gradients could be expected between the capillary zone and the soil surface. However, there is no reason to suppose that large quantities of vapor would translocate from the water table, flow through the persistently dry zone between 70- and 140-cm depth, and into a shallow root zone above 70 cm. The conclusion emerges that panicgrass is an opportunistic phreatophyte.

REFERENCES

Carson, James E., 1963, Analysis of soil and air temperatures by Fourier techniques: Journal of Geophysical Research, v. 68, no. 8, p. 2217-2232.

Culler, R. C., and others, 1970, Objectives, methods, and environment - Gila River Phreatophyte Project, Graham County, Arizona: U.S. Geological Survey Professional Paper 655-A, p. A1-A25.

Leppanen, O. E., 1980, Barren area evapotranspiration estimates generated from energy budget measurements in the Gila River valley of Arizona, U.S. Geological Survey Open-File Report 80-1003, 31 p.

Ripple, C. D., Rubin, J., and van Hylckama, T. E. A., [1972], Estimating steady-state evaporation rates from bare soils under conditions of high water table: U.S. Geological Survey Water-Supply Paper 2019-A, p. A17-A23.

Slatyer, R. O., and McIlroy, I. C., 1961, Practical microclimatology: Melbourne, Commonwealth Scientific and Industrial Research Organization, 310 p.

Turner, R. M., 1974, Quantitative and historical evidence of vegetation changes along the upper Gila River, Arizona: U.S. Geological Survey Professional Paper 655-H, plate 1.