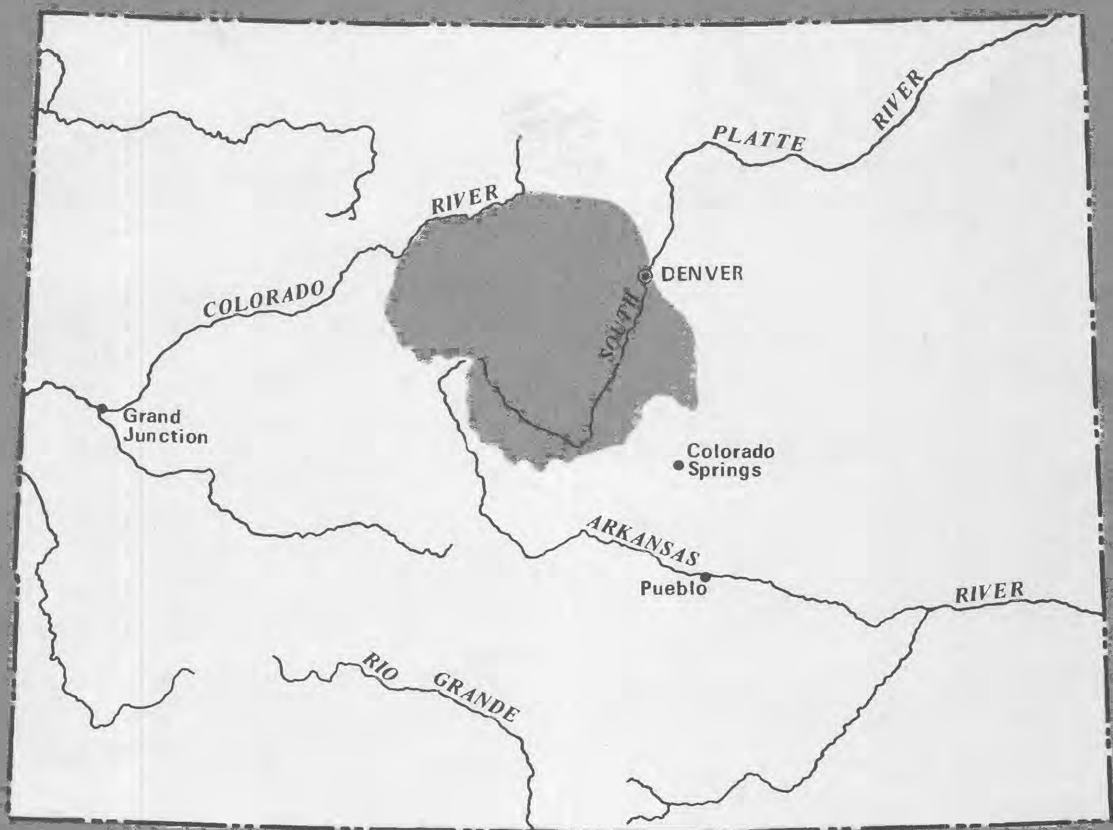
EVAPORATION FROM SEVEN RESERVOIRS IN THE DENVER WATER-SUPPLY SYSTEM, CENTRAL COLORADO

U. S. GEOLOGICAL SURVEY



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16. Abstracts Seven reservoirs in central Colorado, operated by the Denver Board of Water Commissioners, were studied during 1967-73 to determine evaporation losses. These reservoirs, Elevenmile Canyon, Dillon, Gross, Antero, Cheesman, Williams Fork, and Ralston, are located on both sides of the Continental Divide. Methods for computing evaporation include energy-budget, mass-transfer, and pan relationships. Three reservoirs, Elevenmile Canyon, Dillon, and Gross, had mass-transfer coefficients calibrated by energy-budget studies. At the remaining reservoirs,an empirical technique was used to estimate the mass-transfer coefficient. The energy-budget-calibrated methods give the most accurate evaporation values;the empirical coefficients give only a best estimate of evaporation. All reservoirs should be calibrated by energy-budget studies. The pan method of computing evaporation is the least reliable method because of problems of advected energy through the sides of the pan, representative pan exposure, and the irregularity of ratios of reservoir to pan evaporation. Total evaporation for the seasons is not known because instrumentation rafts were not operated during the entire open-water season.

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April 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

SYMBOLS

A Surface area of reservoir

c Specific heat of water

E_{EB} Evaporation computed by the energy-budget method

E_{MT} Evaporation computed by the mass-transfer method

e_a Vapor pressure of the air

e_o Saturation vapor pressure at the temperature of the water surface

L Latent heat of vaporization of water

N Mass-transfer coefficient

P Atmospheric pressure

Q_a	Incoming long-wave radiation
Q_{ar}	Reflected long-wave radiation
Q_{bs}	Long-wave radiation from the water
Q_e	Energy used for evaporation
Q_h	Energy conducted from the water as sensible heat
Q_r	Reflected solar radiation
Q_s	Incoming solar radiation
Q_v	Net energy advected into the lake
Q_w	Energy advected by evaporating water
Q_x	Increase in stored energy
R	Bowen ratio
T_a	Dry-bulb air temperature
T_b	Arbitrary base temperature (0°Celsius) used in energy computations
T_d	Temperature of water at a particular depth, d
T_e	Temperature of evaporated water
T_o	Temperature of the water surface
T_w	Wet-bulb air temperature
T_1	Mean temperature of water at beginning of energy-budget computation period
T_2	Mean temperature of water at end of energy-budget computation period
t	Length of energy-budget computation period
u_z	Windspeed at some height z above the water surface
V	Volume of reservoir
V_1	Volume of water in reservoir at beginning of energy-budget computation period
V_2	Volume of water in reservoir at end of energy-budget computation period
z	Total depth of reservoir
α	Part of additional energy from advection or storage that is used in evaporation
ΔE	Effect on lake evaporation caused by advected or stored energy
γ	Coefficient in the formula used to compute Bowen ratio
ρ	Density of water

METRIC CONVERSION TABLE

Multiply English units	*By*	*To obtain metric units*
inches (in)	25.40	millimeters (mm)
	2.540	centimeters (cm)
inches per day	2.540	centimeters per day (cm/d)
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
miles per hour (mi/h)	4.470×10^{-1}	meters per second (m/s)
square miles (mi^2)	2.590	square kilometers (km^2)
acres	4.047×10^{-3}	square kilometers (km^2)
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometers (hm^3)
calories per gram	4.184×10^{3}	joules per kilogram
calories per square centimeter	4.184×10^{4}	joules per square meter
calories per square centimeter per day (cal cm^{-2} d^{-1})	29.06	watts per square meter
grams per square centimeter per day	10	kilograms per square meter per day
millibars	1.000×10^{2}	newtons per square meter

EVAPORATION FROM SEVEN RESERVOIRS IN THE DENVER WATER-SUPPLY SYSTEM, CENTRAL COLORADO

By John F. Ficke, D. Briane Adams, and Terence W. Danielson

ABSTRACT

Seven reservoirs in central Colorado, operated by the Denver Board of Water Commissioners, were studied to determine evaporation losses. These reservoirs, Elevenmile Canyon, Dillon, Gross, Antero, Cheesman, Williams Fork, and Ralston, are located on both sides of the Continental Divide. The period of study was 1967-73. Evaporation was computed by the energy-budget and mass-transfer methods, and from evaporation-pan relationships. For three reservoirs, Elevenmile Canyon, Dillon, and Gross, mass-transfer coefficients were calibrated by energy-budget studies. At the remaining reservoirs, an empirical technique was used to estimate the mass-transfer coefficient. The energy-budget-calibrated methods give the most accurate evaporation values; the empirical coefficients give only a best estimate of evaporation. The pan method of computing evaporation is the least reliable method because of problems of advected energy through the sides of the pan, representative pan exposure, and the variability of ratios of reservoir to pan evaporation.

Total evaporation for the seasons is not known because instrumentation rafts were not operated during the entire open-water season. Calculation of evaporation (sublimation) amounts from the ice cover was not attempted, but the amounts are believed to be small.

Amounts of evaporation during the longest single period of record at each of the three reservoirs for which energy budgets were determined are:

Elevenmile Canyon Reservoir--	86 centimeters (33.9 inches) in 182 days,
Dillon Reservoir-------------	68 centimeters (26.8 inches) in 155 days, and
Gross Reservoir--------------	63 centimeters (24.8 inches) in 180 days.

Amounts of evaporation during the longest single period of record for each of the four reservoirs where empirical mass-transfer methods were used are:

Antero Reservoir-------------	54 centimeters (21.3 inches) in 161 days,
Cheesman Reservoir-----------	50 centimeters (19.7 inches) in 190 days,
Williams Fork Reservoir------	45 centimeters (17.7 inches) in 155 days, and
Ralston Reservoir------------	66 centimeters (26.0 inches) in 183 days.

Annual ratios of pan evaporation (class-A evaporation pan) to lake evaporation varied from less than 0.5 to more than 0.9. For individual short-term periods of 14 days or less, the ratios ranged from less than 0.3 to more than 4. Ratios generally were smallest in the spring of the year and highest in the fall.

INTRODUCTION

Water supply for 991,000 of the 1.5 million inhabitants of the Denver, Colo., metropolitan area is provided by a complex system of stream diversions and storage reservoirs operated by the Denver Board of Water Commissioners. The Denver metropolitan area is situated in the upper South Platte River basin, on the plains just east of the foothills of the Rocky Mountains and has a semiarid climate. Streamflow patterns in the upper South Platte River basin are characterized by high discharges resulting from snowmelt in the spring and early summer, and by low flows in the late summer, autumn, and winter. Storage reservoirs are a necessity to insure a year-round water supply; however, it is recognized that these same reservoirs can cause sizable water losses through evaporation from their surfaces.

Colorado water law recognizes the significance of evaporation losses from reservoirs by providing for releases from storage in on-stream reservoirs to compensate for evaporation depletions. The statutes state:

> "Upon order of the state engineer there shall be released from the water in storage in each stream bed reservoir such quantities of water as, in the determination of the state engineer, are necessary to prevent evaporation from the surface of such reservoir from depleting the natural flow of the stream running through such reservoir which would otherwise be available for use by other appropriators. In determining the quantity of any evaporation release under this section, the state engineer shall compute the surface evaporation from the reservoir and deduct therefrom any accretions to the stream flow resulting from the existence of the reservoir and any natural depletions to the stream flow which would have resulted if the reservoir were not in existence."

It is therefore desirable to have accurate data on the amount of losses in order that charges for evaporation losses can be equitably assessed.

Evaporation plays another important role in lakes and reservoirs other than the simple water loss--it serves to affect water temperature through evaporative cooling. Energy expended in evaporation of water is taken from the stored heat of the lake, keeping surface temperatures below mean air temperatures throughout the warm season.

Description of Reservoirs Owned by the Denver Board of Water Commissioners

Reservoirs owned by the Denver Board of Water Commissioners are shown on figure 1. Water released from storage reservoirs is conveyed to the city's treatment plants through natural drainages and a system of canals and conduits. Reservoirs on the South Platte River system include Antero Reservoir located near Hartsel about 75 mi (120 km) southwest of Denver, Elevenmile Canyon Reservoir located about 60 mi (96 km) southwest of Denver, and Cheesman Reservoir near Deckers located about 40 mi (64 km) southwest of Denver. Additional water is available to the South Platte River system by diversion from the western side of the Continental Divide. Dillon Reservoir, located on the Blue River at its confluence with Tenmile Creek and the Snake River, impounds water that may be diverted across the Continental Divide through the Harold D. Roberts Tunnel. Water diverted from Dillon Reservoir through the Harold D. Roberts Tunnel enters the North Fork of the South Platte River near Grant, and is transported in the river channel to the South Platte River and then into treatment facilities located in southwest Denver.

Water supply for the northern part of Denver comes mainly from the Fraser and the Williams Fork Rivers, and South Boulder and Ralston Creeks drainage basins. The Fraser and Williams Fork Rivers water, which is diverted across the Continental Divide through the Moffat Tunnel, is discharged into South Boulder Creek and subsequently stored at Gross Reservoir near Eldorado Springs about 30 mi (48 km) northwest of Denver, or Ralston Reservoir near Golden about 10 mi (16 km) northwest of Denver, or used directly by Denver.

To satisfy the demands of senior water rights on the Colorado River, the Denver Board of Water Commissioners is required to replace water that it diverts across the Continental Divide during periods of senior "calls" on the Colorado River. In order to meet this requirement, Williams Fork Reservoir and Power Plant are operated as part of the Denver water-supply system, but water stored in Williams Fork Reservoir is released down the Colorado River rather than being diverted to Denver. Some of the characteristics of the seven storage reservoirs in the Denver Board of Water Commissioners' system are summarized in table 1.

Purposes of Study and Report

This report presents the results of a continuing study conducted by the U.S. Geological Survey in cooperation with the Denver Board of Water Commissioners. Purposes of the study are: (1) To define the amounts of net evaporation losses from the Denver storage reservoirs; and (2) to conduct experiments for improving methods for measuring evaporation, particularly at reservoirs at high elevations.

Acknowledgments

Project planning and operation by the U.S. Geological Survey during the first 3 years (1967-69) of this study were conducted by Stuart Meyers. During 1970-71, the project operation was headed by Alex Sturrock, with the assist-

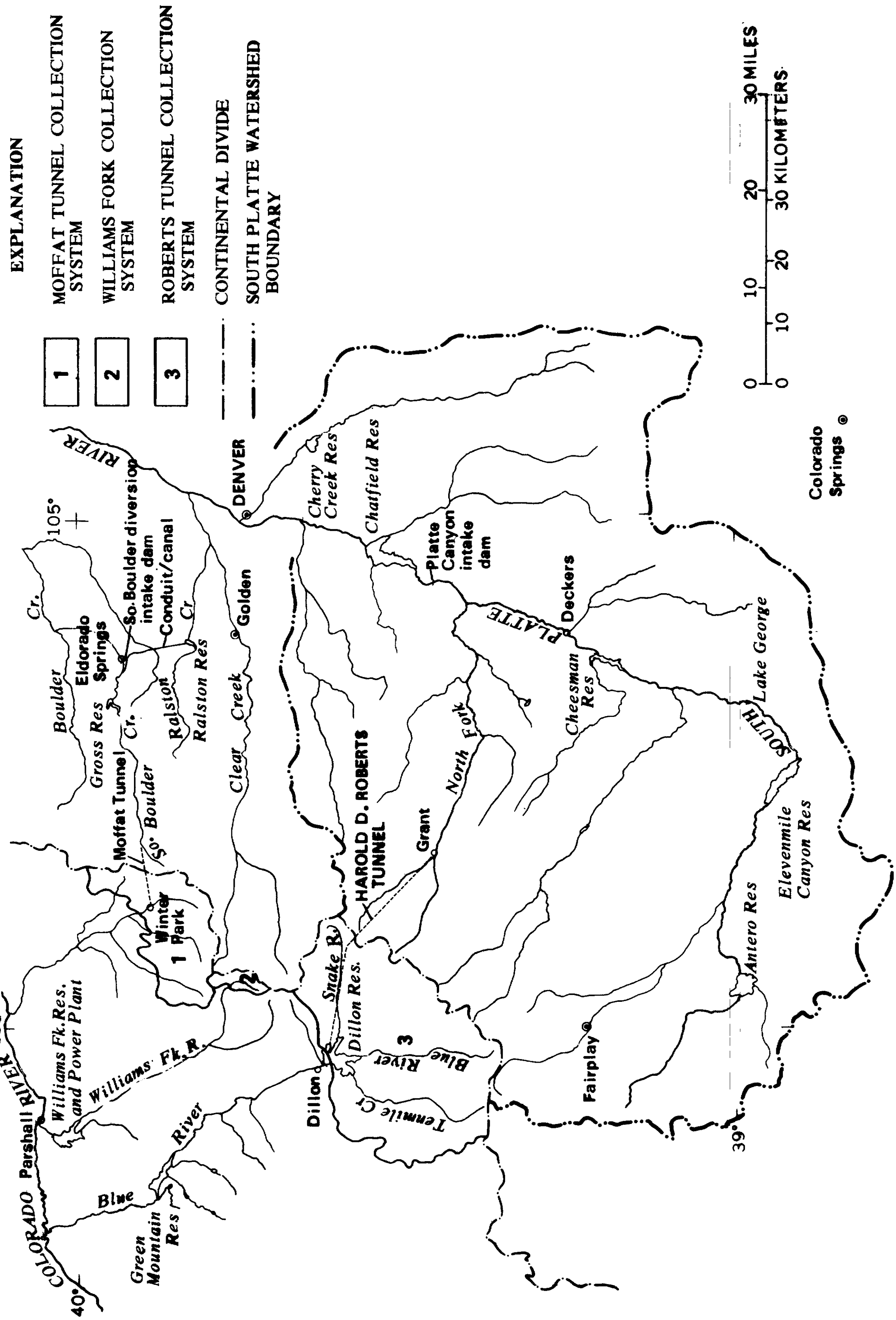

Figure 1.—Water-supply system owned by the Denver Board of Water Commissioners.

Table 1.--*Storage reservoirs in the Denver Board of Water Commissioners' system*

Reservoir	Stream impounded	Year completed	Drainage area (mi^2)	Spillway elevation (ft)	Storage capacity (acre-ft)	Surface area (acres)	Maximum depth (ft)	Mean depth (ft)
Elevenmile Canyon	South Platte River--------	1932	880	8,597	97,779	3,323	117	29.4
Dillon	Blue River and tributaries--	1963	335	9,017	254;036	3,222	188	78.8
Gross	South Boulder Creek--------	1954	93	7,282	41,811	415	297	100.8
Antero	South Platte River--------	1909	337	8,978	15,878	1,931	16	8.2
Cheesman	----do---------	1905	1,752	6,842	79,064	871	212	90.8
Williams Fork	Williams Fork River--------	1959	230	7,803	96,822	1,618	169	59.8
Ralston	Ralston Creek--	1937	46	6,046	11,218	225	151	49.9

ance of Glen Hearne. During the course of the project valuable assistance was provided by Richard Daum, Garth Ghering, and Henry Moore who designed, modified, calibrated, and maintained much of the equipment used on the project. Margaret McNutt and Thomas Devenish contributed substantially to the project operation by processing project records and by assembling parts of the data included in this report.

METHODS FOR COMPUTING EVAPORATION

There are many techniques available for computing evaporation from open-water surfaces. The three techniques selected for use in this project (energy budget, mass-transfer, and evaporation pans) were chosen in order to provide a check of one method against another, and to provide backup data for each other in the event of equipment failure. The methods differ considerably in complexity, accuracy, and cost. It was hoped that through this study a procedure could be derived for computing evaporation with maximum accuracy and minimum cost. Discussions in the following sections describe the characteristics of each computation method, and also discuss the equipment and methods used to collect the data needed to use the different methods.

Several publications are available describing the development and use of the different methods for computing evaporation. Early uses of the energy-budget method on Lake Hefner have been reported by Anderson (1952), and on Lake Mead by Koberg (1958). The mass-transfer technique used was that described by Harbeck (1962). Summaries of techniques for estimating lake evaporation using data from pans have been published by Kohler (1952), and in papers by Kohler, Nordenson, and Fox (1955, 1958), and Kohler, Nordenson, and Baker (1959). Comparison of these methods is presented by Ficke (1972).

Data were collected to compute evaporation using three different techniques. The techniques included the energy-budget method, mass-transfer method, and evaporation from pans. During the course of the study some effort was devoted to the development and improvement of new instrumentation. Results of the instrumentation work are reflected in the data contained in this report; however, this report will not dwell at length in describing the instrumentation research.

Table 2 summarizes the application of the various methods of evaporation measurement on the seven Denver Board of Water Commissioners' reservoirs.

Energy Budget

An energy budget, as its name implies, is an accounting of the gains and losses of energy in a particular system under study. In the case of lakes the equation takes the form

Table 2.--*Summary of techniques used to measure evaporation from the storage reservoirs*

Reservoir	Years in which methods were used		
	Energy budget	Mass transfer	Pan
Elevenmile Canyon--------	1967-70	1967-73	1967-73
Dillon-------------------	1969-71	1969-73	1969-73
Gross--------------------	1972-73	1972-73	1972-73
Antero-------------------	-------	1967-71	1967-71
Cheesman-----------------	-------	1967-73	1967-73
Williams Fork------------	-------	1969-73	1969-73
Ralston------------------	-------	1972-73	1972-73

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_x, \qquad (1)$$

where Q_s = incoming solar radiation,
Q_r = reflected solar radiation,
Q_a = incoming long-wave radiation,
Q_{ar} = reflected long-wave radiation,
Q_{bs} = long-wave radiation from the water,
Q_v = net energy advected into the lake,
Q_e = energy used for evaporation,
Q_h = energy conducted from the water as sensible heat,
Q_w = energy advected by evaporating water, and
Q_x = increase in stored energy.

Energy values in the equation generally are measured in units of calories per square centimeter per day (cal cm^{-2} d^{-1}). Computations normally are made to compute average evaporation over computation periods, which in this project usually were about 14 days.

Values of incoming solar radiation, Q_s, and long-wave radiation, Q_a, were measured directly using radiometers. Reflected solar radiation, Q_r, was estimated as a part of the Q_s values using the relationships developed by Koberg (1964, fig. 36). Reflected long-wave radiation, Q_{ar}, was estimated to be 3.0 percent of the incoming long-wave radiation, Q_a (Anderson, 1952, p. 98). Long-wave radiation from the water surface, Q_{bs}, was determined as a function of the average surface temperature of the lake using the Stefan-Boltzman law with an emissivity of 0.97. Net energy advected, Q_v, was computed using information on temperatures and volumes of inflow, outflow, and precipitation

(World Meteorological Organization, 1966, p. 70-71). Degrees of changes in stored energy, Q_x, were computed using information from thermal surveys conducted at intervals of about 14 days. Additional details on the thermal surveys are provided in a later section of this report.

With direct or computed data on seven of the variables in equation 1, only the terms Q_e, Q_w, and Q_h need to be solved directly. Energy used for evaporation, Q_e, is related to the amount of evaporation by the relationship

$$Q_e = \rho E_{EB} L, \tag{2}$$

where ρ = density of evaporated water, in grams,

E_{EB} = volume of water evaporated as computed by the energy-budget method, in grams per square centimeter per day, and

L = latent heat of vaporization, in calories per gram.

Within the temperature range and accuracy of the data available, density is considered to be 1.0. Latent heat is determined as a function of temperature and values may be found in most physics handbooks. Energy advected by evaporating water is computed as

$$Q_w = \rho c E_{EB} (T_e - T_b), \tag{3}$$

where ρ and E_{EB} are as defined in equation 2,

c = specific heat of water, in calories per gram,

T_e = temperature of evaporated water, in degrees Celsius, C, and

T_b = base of reference temperature, in degrees Celsius (taken as 0°C).

It can be assumed that c is 1.0, T_e is estimated to be equal to the surface temperature of the lake, and T_b is arbitrarily assumed to be 0°C. Conducted sensible heat was estimated as a function of Q_e by use of the Bowen ratio (Bowen, 1926), as

$$Q_h = R Q_e, \tag{4}$$

where R = the Bowen ratio.

The Bowen ratio is computed by the formula

$$R = \frac{\gamma (T_o - T_a) P}{(e_o - e_a) 1{,}000}, \tag{5}$$

where γ = a coefficient equal to about 0.61 in the units used,

T_o = temperature of the water surface, in degrees Celsius,

T_a = air temperature, in degrees Celsius,

e_a = vapor pressure of the air, in millibars,

e_o = saturation vapor pressure at the temperature of the water surface, in millibars, and

P = atmospheric pressure, in millibars.

The several relationships described in equations 2 through 5 can be combined with equation 1 to form

$$E_{EB} = \frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x}{L(1+R)+T_o}. \qquad (6)$$

When the Q terms are in calories per square centimeter per day, evaporation will be in centimeters per day.

Equipment and methods used in this study provided daily mean values for each of the terms in equation 6 except for change in heat storage, Q_x. Values of Q_x could be computed only as averages for the periods between thermal surveys. Therefore, equation 6 could be solved only for each energy-budget computation period, the time between the thermal surveys.

Computer techniques were developed as part of the project to convert instrument records to the forms of data required to solve equation 6. The programs also averaged values over the periods of computation, taking into account the length of the time between thermal surveys. After averaging daily values, the program solves the equation to provide as an answer the average evaporation rate over the computation period, or the total amount of evaporation during the period.

Mass Transfer

Mass-transfer techniques for computing evaporation are considerably more simple to use than the energy-budget method because data requirements, instrumentation, and computation methods are simpler. Of the several mass-transfer equations available, the equation of Harbeck (1962) was used in this study. The relationship is expressed as

$$E_{MT} = Nu_2(e_o-e_a), \qquad (7)$$

where E_{MT} = evaporation, in centimeters per day,

N = an empirical coefficient,

u_2 = average wind speed at 2 meters above water surface, in miles per hour,

e_o = saturation vapor pressure of air at temperature of the water surface, in millibars, and

e_a = vapor pressure of the air, in millibars.

Values of N usually are assumed to be constant for each lake, and must be estimated from some independent measure of evaporation, or from some other factors. Harbeck established that N can be estimated as a function of reservoir area by the relationship

$$N = 0.00859/A^{0.05}, \quad (8)$$

where N is as defined in equation 7, and

A = reservoir surface area, in acres.

However, N includes many other variable factors, such as wind and vapor profiles, wave heights, terrain influences, and surface shape. Preferably, N should be determined from other unbiased measures of evaporation. For Elevenmile Canyon, Dillon, and Gross Reservoirs, the N values were determined by establishing the linear relationship between the energy-budget evaporation, E_{EB}, and the mass-transfer product, $u_2(e_o-e_a)$.

As stated previously, the mass-transfer method for computing evaporation offers the advantages of simplicity and low cost, but these advantages may be lost if N is not known with reasonable accuracy. An additional advantage of the method is its suitability for computing evaporation over short periods of 1 day or less. Ficke (1972) noted that during some periods of very low wind some errors in data may result from anemometer stalling.

Instrumentation and Methods for Data Collection for Energy-Budget and Mass-Transfer Methods

Many of the instruments used during this evaporation study are available commercially. Some of these, however, were modified slightly in order to achieve compatibility, that is, to produce output signals in units suitable for simpler processing. Some others, such as the psychrometers, were of original design (Bellaire and Anderson, 1951) and are not available on the commercial market.

The sketch in figure 2 illustrates some of the equipment used to collect data for energy-budget computations of evaporation from the water-supply reservoirs. The sketch in figure 3 shows the simpler set of equipment used at reservoirs where only the mass-transfer method was used. Equipment and data-collection techniques are described in more detail in the following paragraphs.

Pyranometer.--A 10-junction Eppley pyranometer[1] was used to measure solar

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

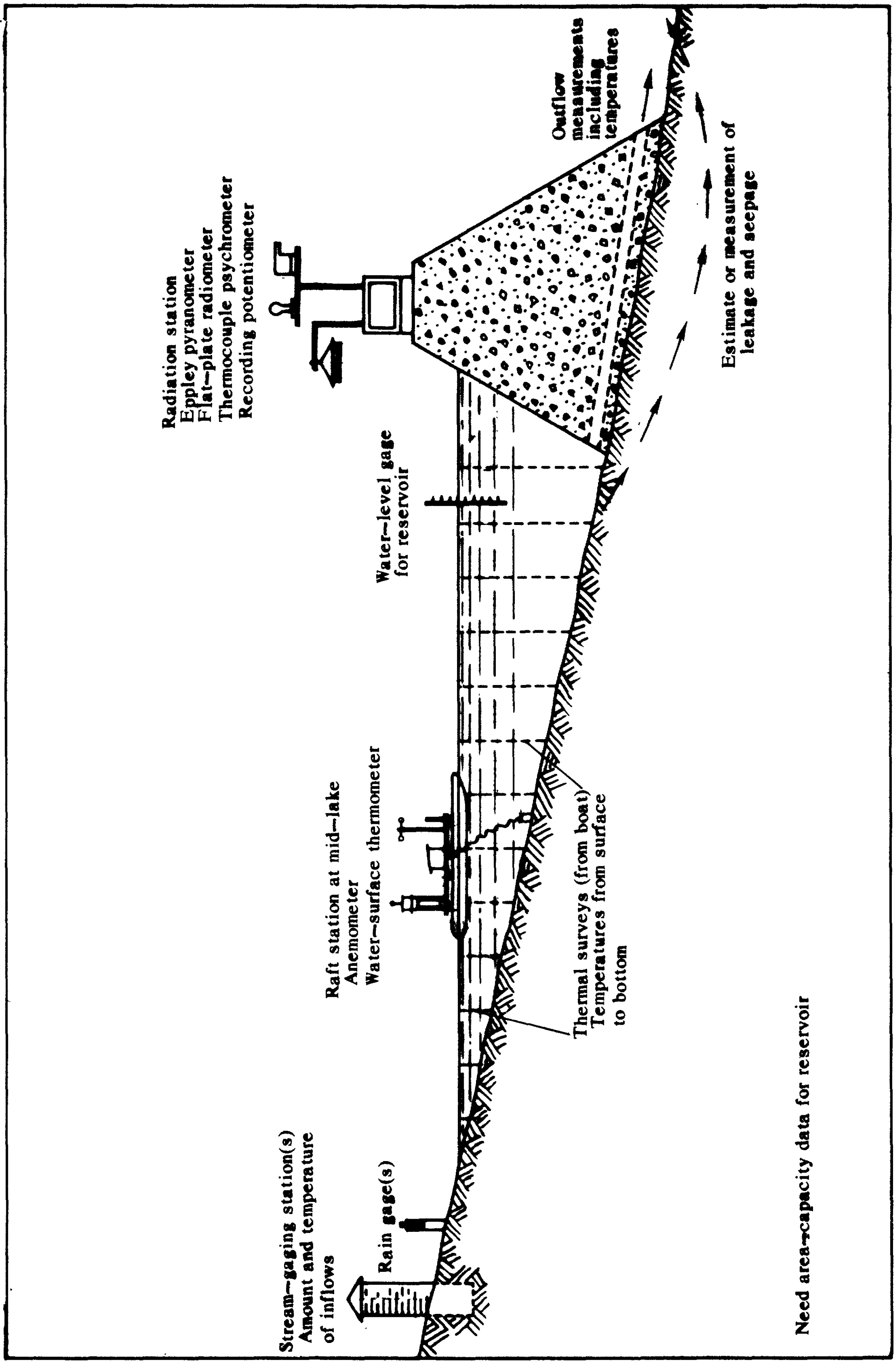

Figure 2.—Equipment used to collect data for computing evaporation by the energy-budget method.

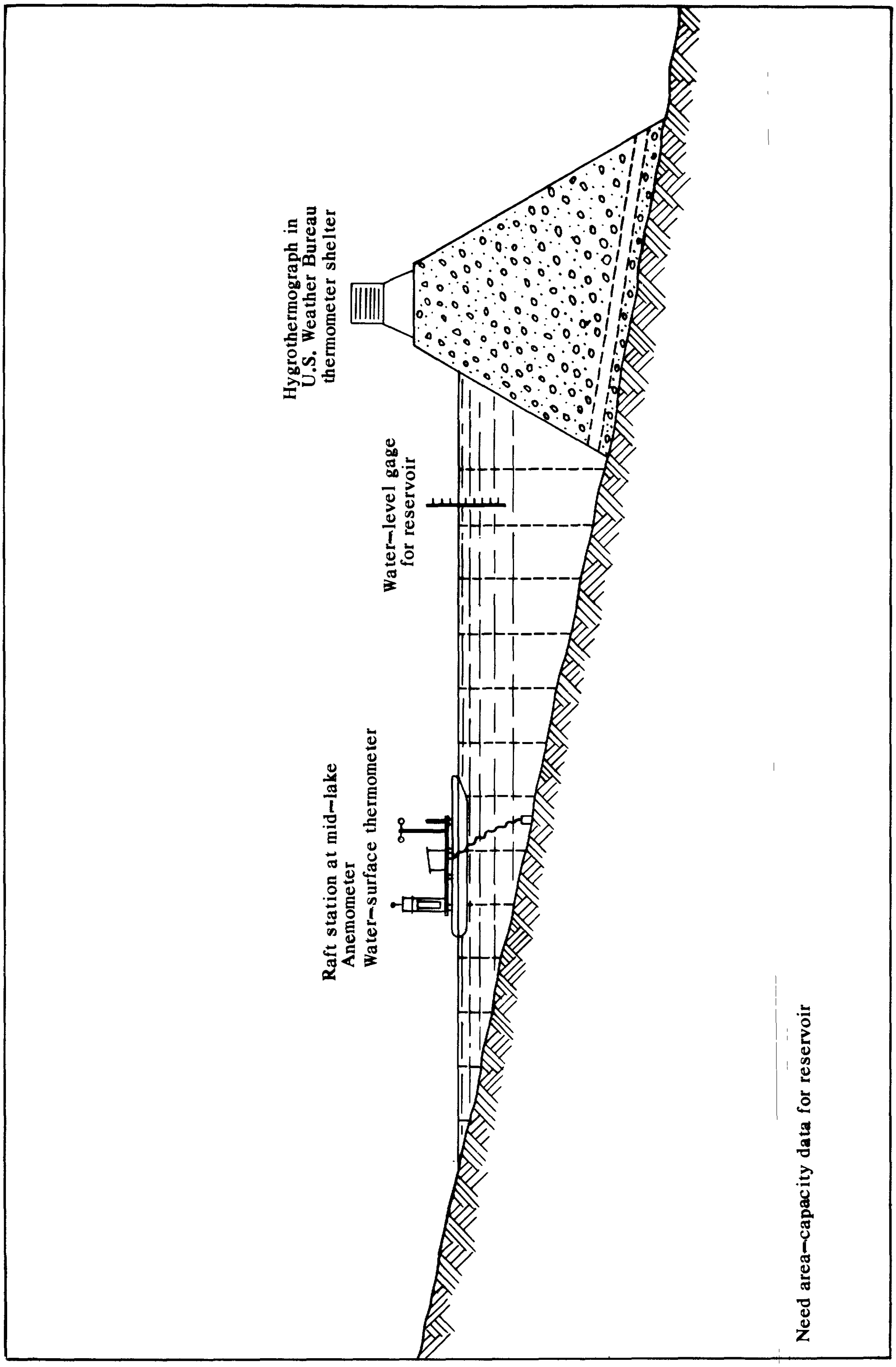

Figure 3.—Equipment used to collect data for computing evaporation by the mass-transfer method.

radiation in all of the energy-budget studies. At Elevenmile Canyon and Gross Reservoirs the instrument was mounted atop the dam. At Dillon Reservoir the instrument was mounted on the shore to the east side of the reservoir. A voltage divider was used to reduce the manufacturer's calibrated output to a convenient scale of 1 millivolt for each 1 cal cm^{-2} min^{-1}. Generally the instruments were calibrated before and after each season's use.

Flat-plate radiometer.--Total long-wave plus short-wave radiation for energy-budget computations was measured by a ventilated total hemispherical flat-plate radiometer. The radiometer is constructed with a thermopile contained in a plate having a black upper surface and a bright lower surface, with continual airflow past the plate being maintained by a motor-driven fan (International Council of Scientific Unions, 1958). Instruments were calibrated and reconditioned with each season's use. The amount of long-wave radiation was computed by subtracting solar radiation measured by the pyranometer from total radiation measured by the flat plate.

Psychrometer.--At reservoirs where the energy-budget method was used, values of air temperature, T_a, and vapor pressure of the air, e_a, were computed from measurements of wet-bulb and dry-bulb temperatures, T_w and T_a, obtained at a thermocouple psychrometer. These data were used in computation of Bowen ratios in energy-budget studies and in the vapor-pressure differences in mass-transfer studies. The psychrometer design of Bellaire and Anderson (1951) and Anderson, Anderson, and Marciano (1950) was followed, with two thermocouples constructed of copper-constantan junctions located beneath a protective radiation shield. A small plastic reservoir held sufficient quantities of water to keep the wick of the wet-bulb thermocouple moist from one servicing to another--a period ranging from twice weekly to once every 2 weeks. At each servicing the psychrometer wicking was cleaned and temperature readings from the thermocouple psychrometer were compared with wet-bulb and dry-bulb readings obtained from sling or power-ventilated psychrometers that used mercury-in-glass thermometers. In most cases the temperatures measured by the two different psychrometers agreed within 0.25°C.

Data from thermocouple psychrometers mounted near the reservoirs were used to compute e_a at Elevenmile Canyon, Dillon, and Gross Reservoirs during the periods when energy-budget data were collected (table 1). For the other reservoirs, and for these three reservoirs at other times, values of e_a were determined from records of hygrothermographs mounted near the reservoirs. Hygrothermographs were carefully calibrated and adjusted in a controlled-humidity laboratory at the beginning of each field season. Calibration was checked during the year by field comparison with humidity measured by wet-bulb and dry-bulb psychrometers. At Dillon and Gross Reservoirs some vapor-pressure data also were collected at lake center using a fan-ventilated thermistor-type psychrometer connected with an amplifier-bridge and digital recorder. The digital-recording psychrometer automatically turned on and off in order to record measurements of wet-bulb and dry-bulb temperatures at 1-hour intervals.

Recorder.--Electrical signals from the pyranometer, flat-plate radiometer, and thermocouple psychrometer were recorded on a single multipoint recording potentiometer. The recorder is designed to switch from one signal to the next at 1-minute intervals, cycling through all the instrument signals, and a reference check once each 8 minutes.

A five-channel, specially-built, integrating device was attached to the recorder to simplify the computation of psychrometric and radiation data. The mechanical device consisted of a series of rotation counters and electrical clutches attached to the moving stylus of the multipoint recorder. As the stylus moved to balance the potentiometer circuit on each signal input from the instrument, the degree of rotation of a counter was proportional to the amplitude of the signal. The total revolution of one of the counters over several cycles is proportional to the integral of one of the measured signals. Therefore, the average of one of the variables, solar radiation, for example, over a period of time could be computed simply from the difference between the readings of the integrator dials taken at the beginning and end of the averaging period divided by the length of the period in proper time units.

Integrator dials generally were read once each day by employees of the Denver Board of Water Commissioners who live at the reservoirs. These frequent, uniformly spaced readings provided daily values of average radiation, air temperature, and vapor pressure for use in the energy-budget equation. Computations of records for 1971 and earlier years generally were by hand manipulation of data using a desk calculator. In 1972 a scheme was developed whereby the daily observed values of dial readings were entered into a computer for automatic computation of daily values of Q_s, Q_r. Q_a, Q_{ar}, T_a, and e_a.

Temperature of the water surface.--Values of water-surface temperature, T_o, are used to compute the Bowen ratio, R; the back radiation from the lake surface, Q_{bs}; and the saturation vapor pressure at the temperature of the water surface, e_o. Temperatures were measured near the center of each lake using a liquid-filled recording thermometer mounted on an anchored raft. The clocks of the recording thermometers were spring-driven and servicing was necessary once each week to wind the clocks and change charts. Instrument calibration was checked with a mercury-in-glass thermometer during each weekly visit. Errors usually were found to be 1°Fahrenheit (0.5°C) or less, and were corrected when the chart records were processed.

Wind speed.--Wind movement at each reservoir was recorded by a three-cup totalizing anemometer mounted on the same raft that was used to hold the instruments for measuring temperature of the water surface. Anemometers were mounted with their cups 6.56 ft (2 m) above the water surface. The totalizing dials on the anemometers generally were read at weekly intervals and the differences between dial readings were used to compute average wind speed during the period between readings.

Advected heat.--Heat is advected to or from a reservoir directly by inflow, outflow, and atmospheric precipitation. Day-to-day variations in temperatures of inflowing and outflowing water were small and computations of average advected heat generally were based on temperatures measured at about weekly intervals. Records of volume of inflow and outflow were provided by personnel of the Denver Board of Water Commissioners, generally based upon streamflow measurements and records from recording stream gages.

Wet-bulb temperatures recorded at the psychrometer at the time of rainfall were used as a measure of the temperature of precipitation. Measurements of precipitation quantity were obtained from rain gages located near the reservoirs and operated by personnel of the Denver Board of Water Commissioners.

Changes in stored energy.--Values of Q_x, in calories per square centimeter per day, for the energy-budget equation can be computed as the change in stored heat over the computation period. An increase in stored heat is considered positive, and generally the quantity is computed as

$$Q_x = c\rho \frac{V_2(T_2-T_b)-V_1(T_1-T_b)}{At}, \qquad (9)$$

where Q_x, c, and ρ are as previously defined;

V_1 and V_2 = volume of water in reservoir at beginning and end of computation period (between thermal surveys), respectively, in cubic centimeters;

T_1 and T_2 = mean temperature of the water at beginning and end of computation period, respectively, in degrees Celsius;

T_b = base temperature, taken to be 0 degrees Celsius;

A = average surface area of reservoir during the computation period (t days), in square centimeters; and

t = the length of the computation period, in days.

With c and ρ equal to 1.0 and T_o assumed to be zero, the equation reduces to

$$Q_x = \frac{V_2T_2-V_1T_1}{At}. \qquad (10)$$

Thermal surveys conducted at intervals of about 2 weeks provided the basis for computing mean temperatures of the lakes. During each survey the variation of water temperature was measured from surface to bottom at each of about 20 measuring sites on the reservoir. Measuring sites were selected to provide a uniform sampling, and were about evenly spaced over the surface of the reservoir in both shallow and deep waters. Temperatures were measured with a resistance-type thermometer that was calibrated over its range against a precision mercury-in-glass thermometer. Field notes from a thermal survey are shown on figure 4.

Mean reservoir temperature for each thermal survey was computed as

$$T = \frac{1}{V} \int_{d=0}^{z} T_d \, dV, \qquad (11)$$

where T = mean temperature of reservoir during thermal survey, in degrees Celsius,

V = volume of reservoir at time of thermal survey, in cubic centimeters,

T_d = temperature of water at depth d, having volume dV, in degrees Celsius, and

z = total depth of reservoir during thermal survey, in centimeters.

A computer printout of the computation of mean temperature from the set of survey notes shown in figure 4 is shown on figure 5.

Evaporation Pans

Evaporation from standard pans frequently is measured in order to estimate evaporation from nearby lakes. Standard U.S. class-A evaporation pans were operated at all of the water-supply reservoirs for the entire period of study at each reservoir (table 2).

Class-A pans.--The class-A pan is a steel tank 4 ft (1.22 m) in diameter and 10 in (255 mm) deep, mounted on a wooden frame platform on the ground. It is filled with water to within 2 in (50 mm) of the top, and each day is refilled to a precise level as determined by a point gage in the tank. The volume of water added at the time of each daily filling is a measure of the amount of water that evaporated from the tank during the 24 hours since the last previous filling. Each pan used in the study was equipped with a totalizing anemometer mounted 6 in (152 mm) above the rim of the pan, and with a maximum-minimum thermometer. Anemometer dials and maximum and minimum temperatures are read and recorded by the observer at the time of each daily filling.

Pan coefficient.--It is common practice to estimate lake evaporation by multiplying the measured pan evaporation by a pan coefficient. If the pan and lake responded identically to meteorological factors such as wind, radiation, and temperature, evaporation rates would be the same and the pan coefficient would be 1.0. However, solar radiation and heat transfer acting upon the sides and bottom of a pan generally produce evaporation rates from a pan that on the average exceed those from a nearby lake. Wind turbulence over the pan also is greater than is turbulence over a lake, thus increasing evaporation. On the average, the ratio of evaporation from a shallow lake to that from a pan (the pan coefficient) is in the range of 0.6 to 0.8. A more detailed description of the factors that affect pan coefficients is presented in reports by Kohler, Nordenson, and Fox (1955) and Kohler, Nordenson, and Baker (1959).

THERMAL SURVEY MEASUREMENT

Lake or reservoir GROSS

Date 10-4-73 Party DANIELSON

Whitney thermom no. W239710

Time at start 0935 Time at finish 1158

Mean hour 1047 Mean gage ht. 7246.49

Auxiliary observations

Time	Gage height	Wtr surf temp		Air temp	Raft	Rdgs of anemom and thermom on raft	
		Whit	Merc			Anem	Ther
0745	246.49						
				49°F			12.8
1225	246.52						
1055						9100.5	

Notes on wind, weather, equipment, etc:

INFLOW ≅ 48 cfs

OUT ≅ 11 cfs

@ 1235 DB = 11.2
WB = 4.9° OK

Found adj screw on Epply loose (not level) - corrected with lock nut

No. 1 of ___ sheets Form C-1, June 65

Figure 4.—Part of a set of field notes from a temperature survey of Gross Reservoir.

9-230-a
(October 1947)
COMPUTATION FORM—DOUBLE

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROSS RESERVOIR THERMAL SURVEY
Oct. 4, 1973

STA / TIME	18 / 9:35	19 / 9:45	20 / 9:50	17 / 10:10	16 / 10:17	15 / 10:21	14 / 10:25	11 / 10:30	12 / 10:34	13 / 10:40	10 / 10:45
0	12.5	12.4	12.2	12.5	12.6	12.7	12.6	12.7	12.8	12.8	12.8
2.5	12.5	12.4	12.1	12.5	12.5	12.6	12.5	12.6	12.6	12.7	12.7
5	12.5	12.4	12.1	12.5	12.5	12.5	12.5	12.5	12.5	12.6	12.5
7.5	12.5	12.4	12.0	12.5	12.4	12.5	12.5	12.5	12.5	12.5	12.5
10	12.5	12.4	12.0	12.5	12.4	12.5	12.5	12.5	12.5	12.5	12.5
15	12.5	12.4	11.8	12.4	12.4	12.4	12.5	12.5	12.5	12.5	12.5
20	12.5	12.3	8.5	12.4	12.4	12.4	12.5	12.5	12.5	12.5	12.5
25	12.5	12.1		12.4	12.4	12.4	12.5	12.4	12.5	12.5	12.5
30	12.5	12.0		12.4	12.4	12.4	12.5	12.4	12.5	12.5	12.5
35	12.5			12.4	12.4	12.4	12.4	12.4	12.5	12.5	12.5
40	12.5			12.4	12.4	12.4	12.4	12.4	12.5	12.5	12.5
45	12.5			12.4	12.4	12.4	12.4	12.4	12.5	12.4	12.5
50	12.4			12.4	12.4	12.4	12.4	12.4	12.5	12.4	12.4
60	12.2			12.3	12.3	12.4	12.4	12.4	12.3	12.4	12.3
70	11.8			12.0		12.3	12.2	12.3	12.2	12.2	12.2
80						11.8	12.1		12.1	12.1	12.0
90						11.5	12.0		12.0	12.0	11.9
100							11.9		11.9	11.9	11.8
120									11.7	11.7	11.7
140									11.5		
160											
180											
200											
220											
Bottom / TEMP	77 / 11.5	34 / 9.2	22 / 7.4	77 / 10.0	66 / 12.2	92 / 11.1	106 / 11.9	78 / 12.3	145 / 11.5	130 / 11.7	132 / 11.6

INLET TEMP = 3.3
OUT 51°F

Figure 4.—Part of a set of field notes from a temperature survey of Gross Reservoir—Continued.

FILE

9 / 10:50	RAFT / 11:15	6 / 11:22	5 / 11:27	7 / 11:33	8 / 11:38	3 / 11:47	1 / 11:51	2 / 11:58			
12.9	12.8	12.6	12.6	12.6	12.6	12.8	12.9	12.8			12.7
12.7	12.7	12.6	12.6	12.6	12.6	12.8	12.8	12.8			12.6
12.6	12.5	12.4	12.5	12.6	12.5	12.7	12.5	12.6			12.5
12.5	12.5	12.4	12.4	12.6	12.4	12.6	12.4	12.5			12.5
12.5	12.4	12.4	12.4	12.5	12.3	12.5	12.4	12.4			12.4
12.5	12.4	12.3	12.4	12.4	12.2	12.4	12.4	12.4			12.4
12.5	12.4	12.3	12.3	12.4	12.2	12.4	12.4	12.4			12.2
12.5	12.4	12.3	12.3	12.4	12.2	12.4	12.4	12.4			12.4
12.5	12.4	12.3	12.3	12.3	12.2	12.4	12.4	12.4			12.4
12.5	12.4	12.3	12.3	12.3	12.2	12.4	12.4	12.4			12.4
12.5	12.4	12.3	12.3	12.3	12.1	12.4	12.4	12.4			12.4
12.5	12.4	12.3	12.3	12.3	12.1	12.3	12.4	12.4			12.4
12.4	12.4	12.3	12.3	12.3		12.3	12.4	12.4			12.4
12.4	12.3	12.2	12.3	12.2			12.3	12.3			12.3
12.2	12.2	12.0	12.1	12.2			12.1	12.1			12.1
12.0	12.0	12.0	11.9	12.1			12.0	11.9			12.0
11.9	11.9	11.9	11.9	11.9			11.8	11.8			11.9
11.8	11.8	11.8	11.7				11.8	11.8			11.8
11.7	11.6	11.6	11.6				11.6	11.6			11.6
	11.4						10.4				11.1
	11.3										11.3
	11.1										11.1
	11.0								Nobs = 25		11.0
	11.0										11.0
135 / 11.1	235 / 11.0	134 / 11.5	136 / 11.5	97 / 11.9	48 / 12.1	56 / 12.3	140 / 10.4	126 / 11.6			

Figure 4.—Part of a set of field notes from a temperature survey of Gross Reservoir—Continued.

GROSS RESERVOIR THERMAL SURVEY OF OCTOBER 4, 1973
NOBS= 25 GHDAY= 7246,50

DOBS	GHO	VOL	VOLINC	TEMP	TEMINC	HTINC
0,0	7246.50	28794.		12,70		
			798.		12,65	10095.
2,5	7244.00	27996.		12,60		
			781.		12,55	9795.
5,0	7241.50	27216.		12,50		
			767.		12,50	9581.
7,5	7239,00	26449.		12,50		
			752.		12,45	9362.
10.0	7236.50	25697.		12,40		
			1461.		12,40	18116.
15,0	7231,50	24236.		12,40		
			1403.		12,30	17251.
20,0	7226.50	22834.		12,20		
			1346.		12.30	16550.
25,0	7221.50	21488.		12,40		
			1289.		12,40	15977.
30,0	7216.50	20200.		12,40		
			1239.		12,40	15357.
35,0	7211.50	18961.		12,40		
			1187.		12,40	14719.
40,0	7206,50	17774.		12,40		
			1128.		12,40	13981.
45,0	7201.50	16647.		12,40		
			1076.		12,40	13342.
50,0	7196.50	15571.		12,40		
			2007.		12,35	24780.
60.0	7186,50	13564.		12,30		
			1822.		12.20	22228.
70,0	7176.50	11742.		12,10		
			1636.		12,05	19714.
80,0	7166.50	10106.		12,00		
			1462.		11,95	17471.
90,0	7156.50	8644.		11,90		
			1306.		11,85	15470.
100,0	7146.50	7339.		11,80		
			2151.		11,70	25167.
120,0	7126.50	5188.		11,60		
			1685.		11,35	19125.
140,0	7106.50	3503.		11,10		
			1300.		11,20	14560.
160,0	7086,50	2203.		11,30		
			963.		11,20	10780.
180,0	7066,50	1240.		11,10		
			654.		11,05	7227.
200,0	7046,50	586.		11,00		
			397.		11,00	4367.
220,0	7026,50	189.		11,00		
			189.		9,20	1737.
260,5	6986.00	0.		7,40		
			28794.			346752.

AREA= 322.0 ACRES 0,13031E 11SQUARE CM HEAT= 0,42772E 15CALORIES

ENERGY STORAGE= 32824.CAL/SQCM AVE TEMP=12,04DEGREES C

Figure 5.—Printout of a computation of heat storage and mean temperature in Gross Reservoir.

Advected and stored energy.--Pan coefficients for deep lakes vary considerably from season to season because of heat storage in the water mass. The coefficients also are influenced by advected energy; and in the cases of Denver reservoirs, which have large volumes of inflows and outflows, these effects can be large. Three terms of the energy-budget equation (equation 1) represent the advected and stored energy that distorts the pan coefficient. These terms are Q_v, net advected energy from precipitation, inflow, and outflow; Q_w, energy advected by evaporating water; and Q_x, increase in stored energy. However, not all of the energy represented by Q_v, Q_w, and Q_x results in direct influence on the pan coefficient--part of it is dissipated or compensated by adjustment of other terms of the energy budget. Net effects on lake evaporation, ΔE, is computed as

$$\Delta E = \frac{\alpha(Q_v - Q_w - Q_x)}{L}, \qquad (12)$$

where L and Q are as previously defined,

ΔE = evaporation effect, in centimeters, and

α = a coefficient.

Relationships for estimating α have been reported by Kohler, Nordenson, and Fox (1955) and by Harbeck (1964).

EVAPORATION FROM ELEVENMILE CANYON RESERVOIR

Elevenmile Canyon Reservoir is located on the South Platte River about 60 mi (96 km) south-southwest of Denver (fig. 1). Water is impounded by a gravity-arch concrete dam which was completed in 1932. When full, the water surface in the reservoir is at an altitude of 8,597 ft (2,619 m) above sea level; the reservoir contains 97,779 acre-ft (120.5 hm^3) of water and has a surface area of 3,323 acres (13.4 km^2).

Evaporation studies of Elevenmile Canyon Reservoir were begun in 1967. Energy-budget studies were conducted for 4 years, 1967-70. Evaporation measurement by the mass-transfer method and by standard class-A pan were conducted for 7 years, 1967-73.

Data for energy-budget computation, including air temperature (wet bulb and dry bulb) and radiation, were measured with instruments located atop the dam. Measurements of air temperature, relative humidity, and pan evaporation used in mass-transfer and pan studies were made at instruments located about 500 ft (152 m) downstream from the dam. Temperatures of the reservoir surface and average wind speed were measured by instruments attached to a raft anchored near the center of the reservoir.

Energy-Budget Parameters

Data for solar radiation, Q_s, are from a pyranometer installed at the top of the dam. Short periods of missing pyranometer data were filled in by estimates based upon tabulated values of clear sky radiation and observed cloud cover. A time graph of solar-radiation, Q_s, values recorded at Elevenmile Canyon Reservoir during 1970 is shown on figure 6. The values are based upon daily integrator readings from the recorder.

Records of wet-bulb and dry-bulb temperatures were computed largely from the integrator records of the recorder connected to the thermocouple psychrometer described earlier. Except for minor difficulties caused by broken thermocouple leads, the records were quite complete. It was difficult to evaluate the effect of freezing upon the wet-bulb temperature record. Consequently, most vapor-pressure records for periods of psychrometer reservoir freezing were estimated from hygrothermograph records at the reservoir. As indicated by the vapor-pressure records (fig. 7), the values of air vapor pressure (e_a) were recorded daily and were then averaged over the number of days between thermal surveys for computation of evaporation. Errors could be expected to result from this type of computation because the relationship between temperature and vapor pressure is not linear. On the other hand, the errors are small and the cost of additional accuracy afforded by more frequent thermal surveys could not be justified.

Values of saturation vapor pressure at the temperature of the water surface (e_o) were selected from tables of the saturation vapor pressure of water, as functions of daily mean surface temperature (T_o) (fig. 8) computed from records of the thermograph or thermistor on the raft in the center of the lake. Record of e_o for 1970 is also shown in figure 7.

Temperature-survey data were used to compute the mean temperature in each layer measured. The energy in each layer, measured above a base of 0°C, was computed as the product of temperature and the volume of the layer. Finally, average storage, in calories per square centimeter, was computed as the sum of the individual layers divided by the surface area of the reservoir. Changes in stored energy between any two surveys, divided by the length of the period, yielded the term Q_x, in calories per square centimeter per day (see equation 10).

Volumes used in the computation of energy storage were computed from a capacity table supplied by the Denver Board of Water Commissioners. Computation of evaporation would not be affected by errors in the capacity table during those periods when there is little or no change in heat storage. The greatest error would be expected during periods of rapid heating during the spring and early summer.

It is obvious that reliable values of Q_x can be computed only between two accurate measurements of energy storage. Consequently, solutions of the energy-budget formula are limited to those periods between major temperature surveys.

Volume and temperature records for rainfall, inflow, and outflow were used to compute advected energy (Q_v). Advected energy is a relatively small term in the energy budgets of reservoirs having large ratios of volume/flow-through.

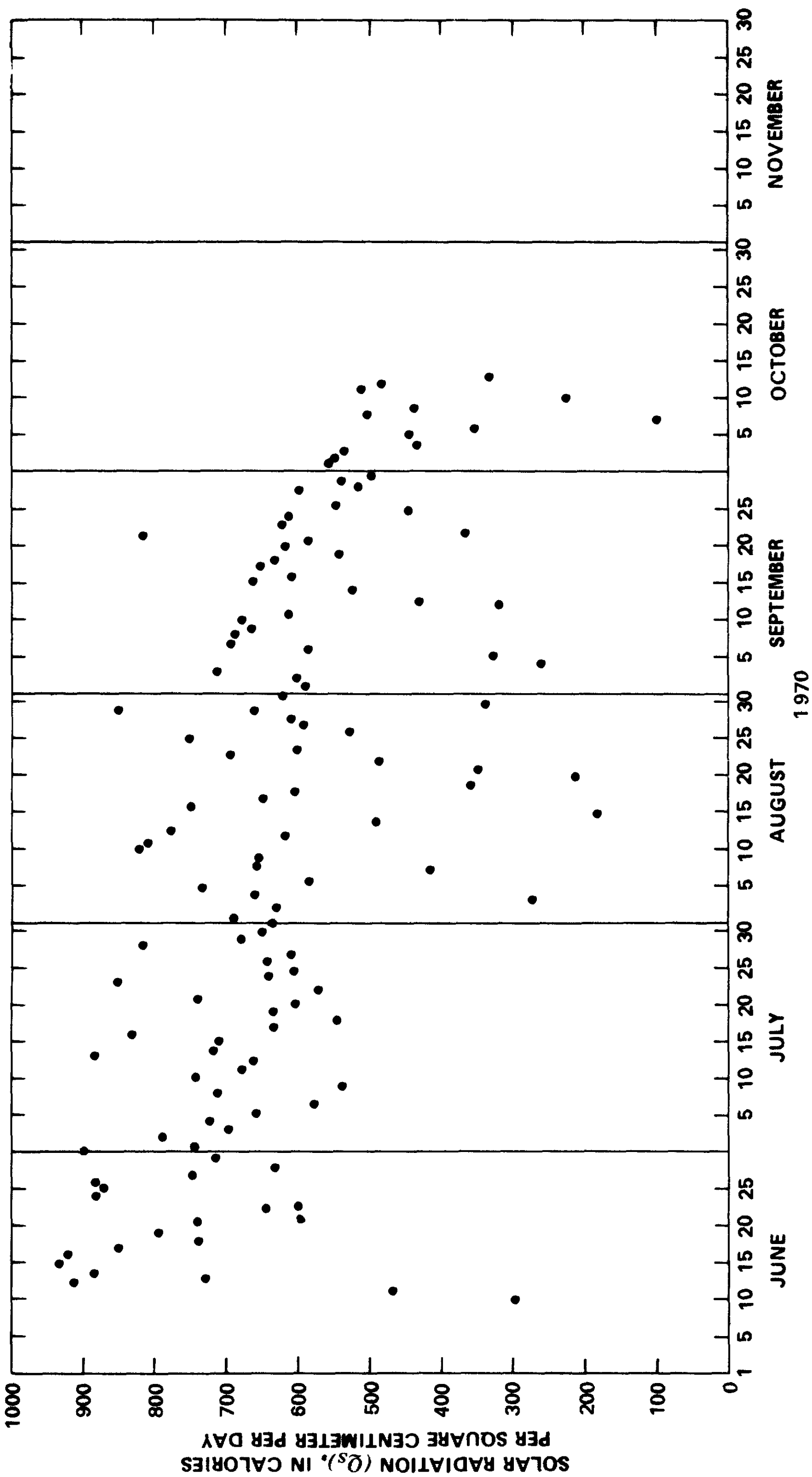

Figure 6.—Time graph of solar radiation, Q_S, measured at Elevenmile Canyon Reservoir.

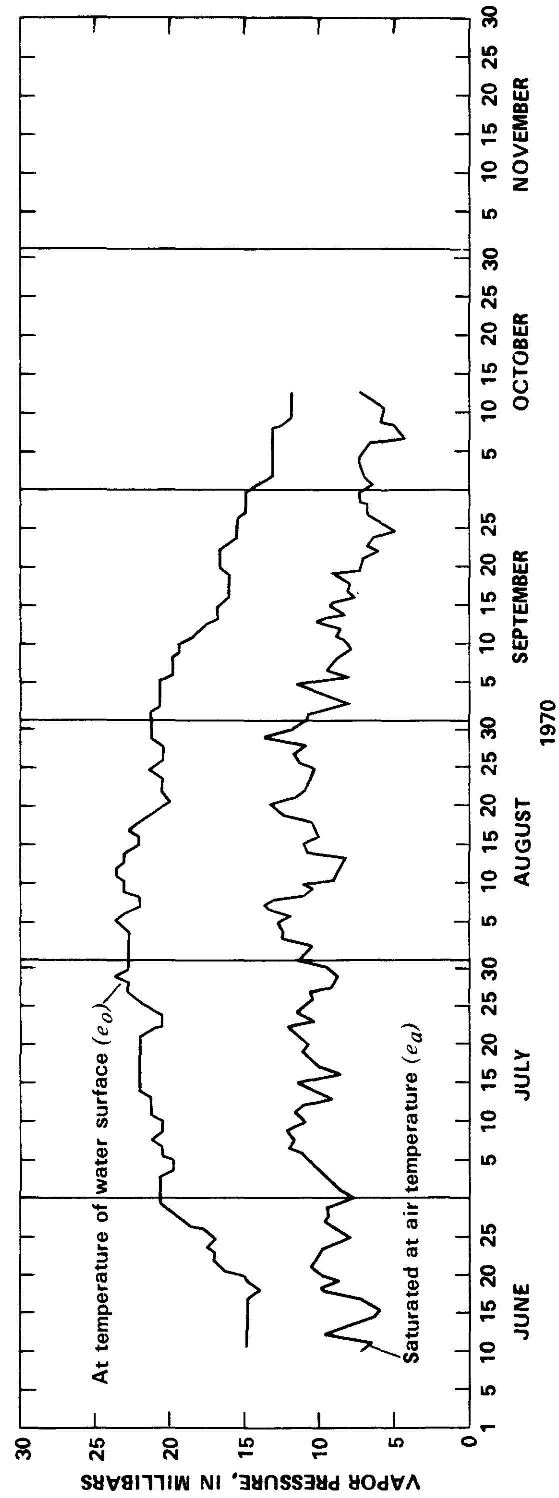

Figure 7.—Time graph of vapor pressures, e_o and e_a, at Elevenmile Canyon Reservoir.

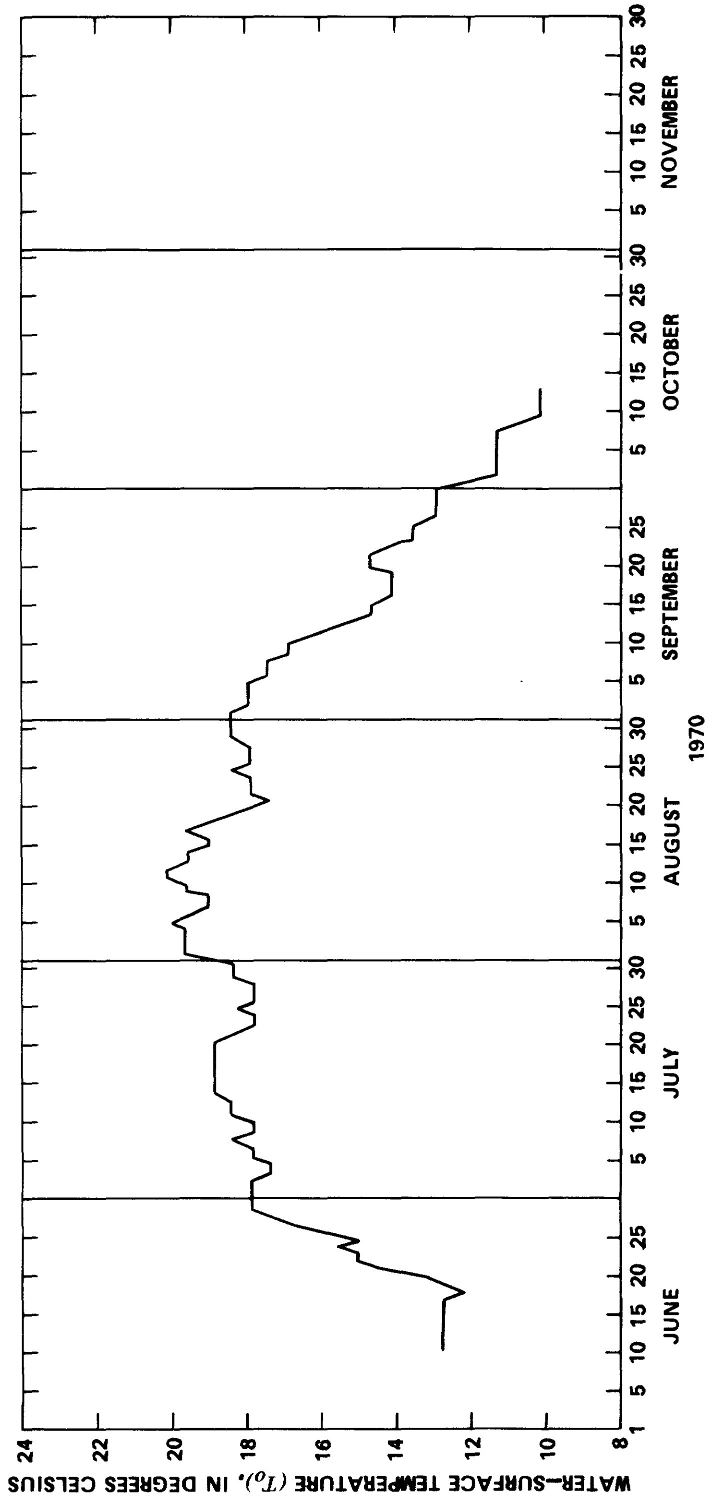

Figure 8.—Time graph of water-surface temperature, T_O, of Elevenmile Canyon Reservoir.

In reporting values of Q_v, it sometimes is convenient to combine the Q_v data with data on changes in energy storage (Q_x), and to report the difference (Q_v-Q_x). The combination Q_v-Q_x represents the combined last two terms of the numerator in equation 6. Values of Q_v-Q_x for Elevenmile Canyon Reservoir for the 1970 record season are shown in figure 9.

Energy-Budget Records

Energy-budget records for Elevenmile Canyon Reservoir for 1967-70 are summarized in table 3. Evaporation rates for the period also are shown graphically by the evaporation hydrographs on figure 10. Data are summarized according to periods between thermal surveys. Most of these periods were 14 days long, but length ranged from 5 to 21 days.

Evaporation rates during the computation periods ranged from 0.200 to 0.674 cm/d. Seasonal average rates for the periods of record ranged from the low of 0.413 cm/d for 1968 to the high of 0.550 cm/d for 1970. However, average rates for the different record seasons are not directly comparable because of differences in the dates of the record periods from year to year.

Mass-Transfer Records

Calibration of the coefficient.--Data for the energy-budget studies of 1967-70 were used to calibrate the mass-transfer coefficient, N (see fig. 11), for Elevenmile Canyon Reservoir. Figure 11 shows the values of evaporation rates measured by the energy budget, E_{EB}, plotted against the mass-transfer product $u_2(e_o-e_a)$. The slope of the relation line defined by the plot in figure 11 will be equal to the value of N.

Several different methods were used to determine the value of N from the data defined in figure 11. The values, as determined by different methods, are summarized in figure 12, where the ratio technique refers to the slope of a line passing through the origin and through the means of the two variables of figure 11, E_{EB} and $u_2(e_o-e_a)$. Weighted ratios were computed considering the lengths of the periods, and obviously are very nearly the same as the unweighted ratios. Results of unweighted, weighted, and double-weighted regressions also are summarized in figure 12. Dashed horizontal lines in the figure represent 95-percent confidence limits for the regression coefficients.

Based upon the results shown in figure 12, a value of N of 0.00800 was selected for Elevenmile Canyon Reservoir. However, the plot shows that 1968 data defined an N value about 15 percent less than the mean and 1970 data showed a value about 15 percent greater than the mean. Different annual patterns also seem to be indicated by the patterns of the data as they are plotted on figure 11. However, a careful examination of the records for 1967-70 did not reveal an explanation of the large variations in N from year to year.

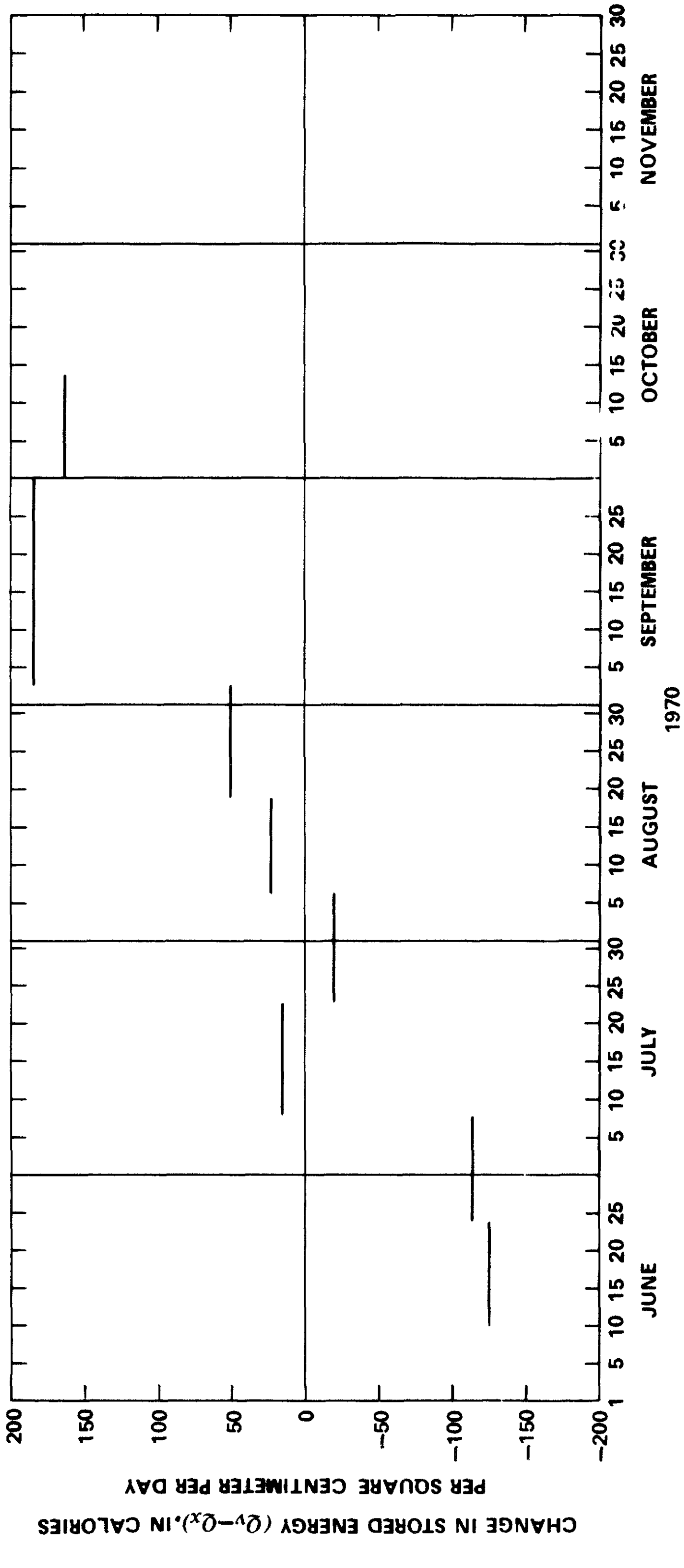

Figure 9.—Time graph of advected energy minus changes in stored energy, $Q_v - Q_x$, for Elevenmile Canyon Reservoir.

Table 3.--*Summary of energy-budget terms and evaporation computation for Elevenmile Canyon Reservoir*

No.	Length (days)	Period: Dates 1967	Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation: Centimeters per day	Evaporation: Centimeters per period
			Cal cm^{-2} d^{-1}											
1	14	May 3- May 17	639	42	558	702	1	139	258	54	3	0.211	0.435	6.09
2	14	May 17- May 31	582	37	595	735	9	111	258	40	5	.155	.438	6.13
3	14	May 31- June 14	591	37	625	754	6	113	259	53	5	.205	.440	6.16
4	14	June 14- June 28	584	37	681	773	7	125	286	44	7	.154	.486	6.80
5	12	June 28- July 10	628	38	709	797	14	147	332	28	9	.083	.566	6.79
6	16	July 10- July 26	597	37	689	816	18	71	321	49	10	.152	.548	8.77
7	14	July 26- Aug. 9	559	36	692	829	13	21	319	48	11	.151	.545	7.63
8	14	Aug. 9- Aug. 23	520	35	609	819	10	-118	314	80	10	.254	.535	7.49
9	14	Aug. 23-Sept. 6	523	35	630	799	4	- 40	295	59	8	.201	.503	7.04
10	14	Sept. 6-Sept. 20	461	33	601	775	- 5	-101	280	63	7	.225	.476	6.66
11	14	Sept. 20- Oct. 4	485	37	580	764	1	- 37	263	33	6	.124	.447	6.26
12	14	Oct. 4- Oct. 18	392	33	523	748	1	-136	211	55	4	.260	.359	5.03
13	14	Oct. 18- Nov. 1	362	32	488	722	- 2	-188	210	69	3	.330	.355	4.97
Record season	182	May 3- Nov. 1	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	0.472	85.82

Table 3.--*Summary of energy-budget terms and evaporation computation for Elevenmile Canyon Reservoir*--Continued

Period													Evaporation	
No.	Length (days)	Dates 1968	Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Centi- meters per day	Centi- meters per period
			Cal cm^{-2} d^{-1}											
14	5	May 17- May 22	765	45	441	708	2	311	118	24	2	0.205	0.200	1.0
15	14	May 22- June 5	720	44	488	727	6	255	181	4	3	.023	.309	4.33
16	14	June 5- June 19	778	45	496	764	10	168	276	25	6	.090	.469	6.57
17	14	June 19- July 3	806	46	515	791	15	81	393	15	11	.037	.670	9.38
18	14	July 3- July 17	666	43	558	802	16	107	252	30	7	.117	.430	6.02
19	14	July 17- July 31	541	45	574	811	12	15	219	31	7	.142	.373	5.22
20	15	July 31- Aug. 15	494	34	591	812	18	9	199	43	6	.215	.340	5.10
21	13	Aug. 15- Aug. 28	707	44	516	804	0	- 62	378	48	11	.127	.644	8.37
22	14	Aug. 28-Sept. 11	606	41	506	794	- 3	- 87	212	52	6	.244	.484	6.76
23	14	Sept. 11-Sept. 25	577	40	476	767	1	-121	296	65	7	.220	.501	7.01
24	14	Sept. 25- Oct. 9	445	36	478	747	0	- 97	187	47	4	.249	.316	4.42
25	21	Oct. 9- Oct. 30	416	34	428	724	- 1	-141	175	48	3	.272	.296	6.22
Record season	166	May 17- Oct. 30	---	---	---	---	---	---	---	---	---	---	0.424	70.40

Table 3.--*Summary of energy-budget terms and evaporation computation for Elevenmile Canyon Reservoir*--Continued

Period				Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation	
No.	Length (days)		Dates 1969	Cal cm^{-2} d^{-1}										Centi-meters per day	Centi-meters per period
26	13	May	7- May 20	694	45	508	733	2	172	207	45	4	0.225	0.345	4.48
27	15	May	20- June 4	642	42	549	754	13	115	251	37	5	.146	.426	6.39
28	14	June	4- June 18	503	34	548	766	24	7	205	59	5	.288	.347	4.86
29	14	June	18- July 2	786	46	534	770	7	119	340	44	8	.129	.576	8.06
30	14	July	2- July 16	646	38	596	795	18	128	272	20	7	.072	.462	6.47
31	14	July	16- July 30	599	37	637	818	26	88	275	35	9	.129	.466	6.52
32	14	July	30- Aug. 13	666	43	629	834	17	48	337	39	11	.115	.575	8.05
33	14	Aug.	13- Aug. 27	606	41	597	825	12	- 39	316	62	10	.197	.538	7.53
34	14	Aug.	27-Sept. 10	488	34	594	812	1	- 79	257	52	8	.202	.437	6.12
35	14	Sept.	10-Sept. 24	442	32	545	788	- 4	-129	220	67	6	.303	.373	5.22
36	14	Sept.	24- Oct. 8	439	35	478	767	- 2	-200	219	89	5	.407	.371	5.19
37	14	Oct.	8- Oct. 22	346	28	473	719	-13	-284	195	145	3	.746	.329	4.61
Record season	168	May	7- Oct. 22	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	0.438	73.50

Table 3.--*Summary of energy-budget terms and evaporation computation for Elevenmile Canyon Reservoir*--Continued

Period			Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation	
No.	Length (days)	Dates 1970	Cal cm^{-2} d^{-1}										Centimeters per day	Centimeters per period
38	14	June 10- June 24	720	44	558	761	47	173	309	32	7	0.102	0.623	7.31
39	14	June 24- July 8	725	44	624	850	39	154	366	10	11	.028	.547	8.70
40	15	July 8- July 23	677	43	628	860	52	40	396	47	12	.118	.613	10.10
41	14	July 23- Aug. 6	649	42	634	809	35	57	343	38	11	.112	.610	8.17
42	13	Aug. 6- Aug. 19	613	41	628	813	27	6	339	45	11	.132	.596	7.50
43	14	Aug. 19-Sept. 2	525	35	620	807	10	- 37	279	56	9	.202	.483	6.65
44	14	Sept. 2-Sept. 16	550	39	550	798	6	-175	350	84	10	.241	.595	8.32
45	14	Sept. 16-Sept. 30	560	40	501	766	8	-173	316	112	7	.356	.536	7.51
46	14	Sept. 30- Oct. 14	423	35	497	737	- 8	-170	214	92	4	.429	.363	5.07
Record season	126	June 10- Oct. 14	------	------	------	------	------	------	------	------	------	------	0.550	69.33

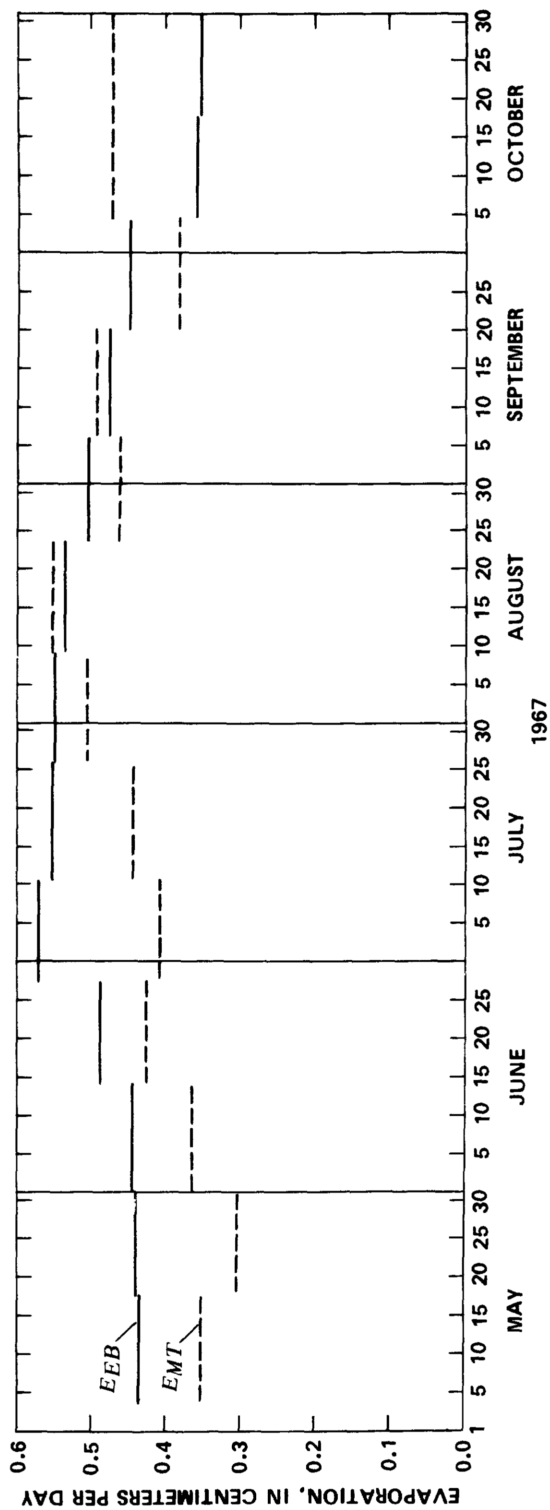

Figure 10.—Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Elevenmile Canyon Reservoir for the 1967–70 record seasons.

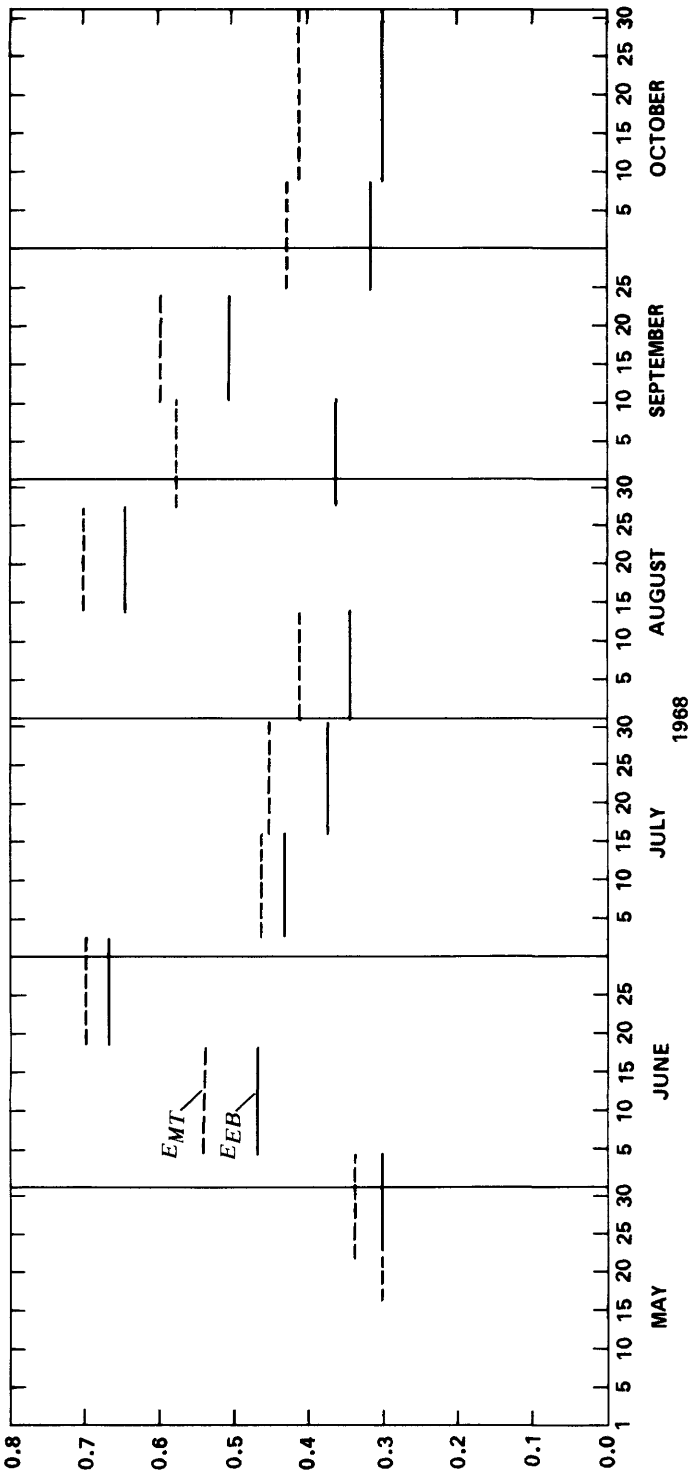

Figure 10.--Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Elevenmile Canyon Reservoir for the 1967-70 record seasons--Continued.

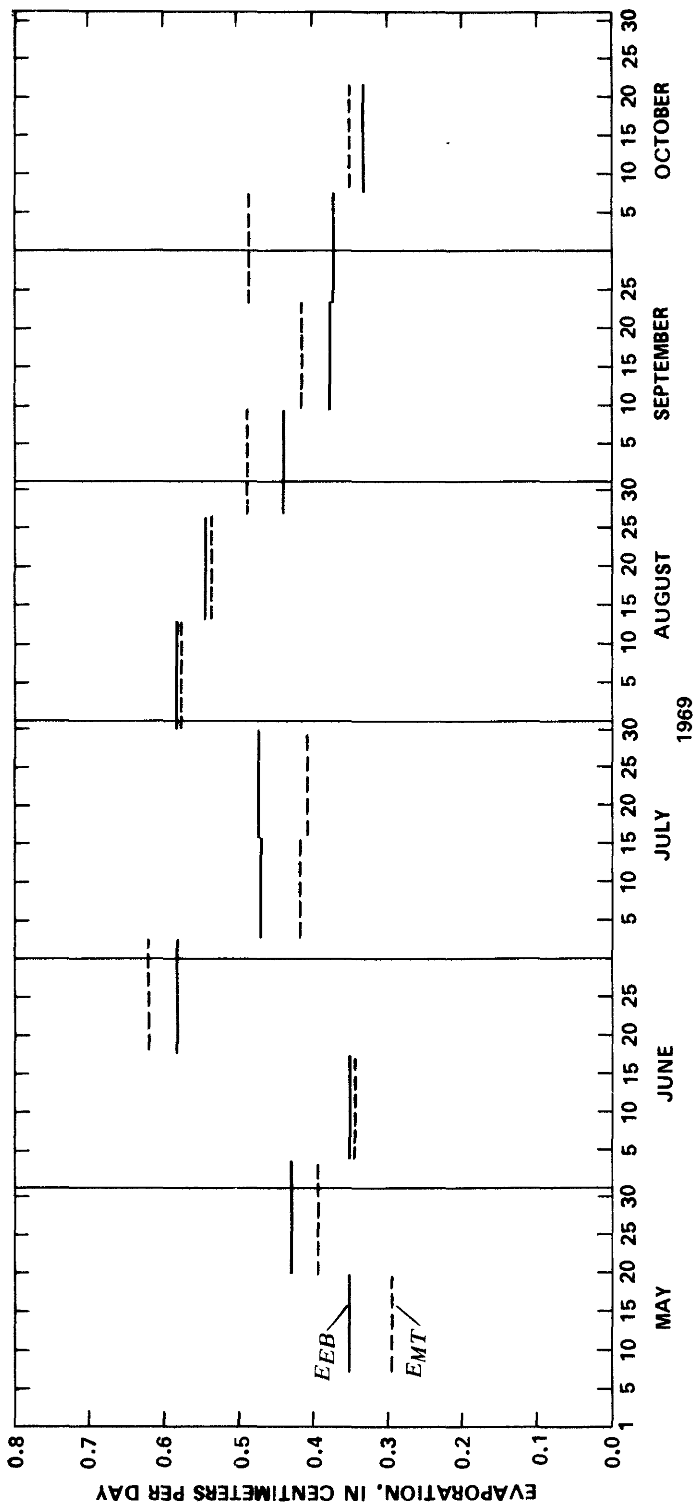

Figure 10.--Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Elevenmile Canyon Reservoir for the 1967-70 record seasons--Continued.

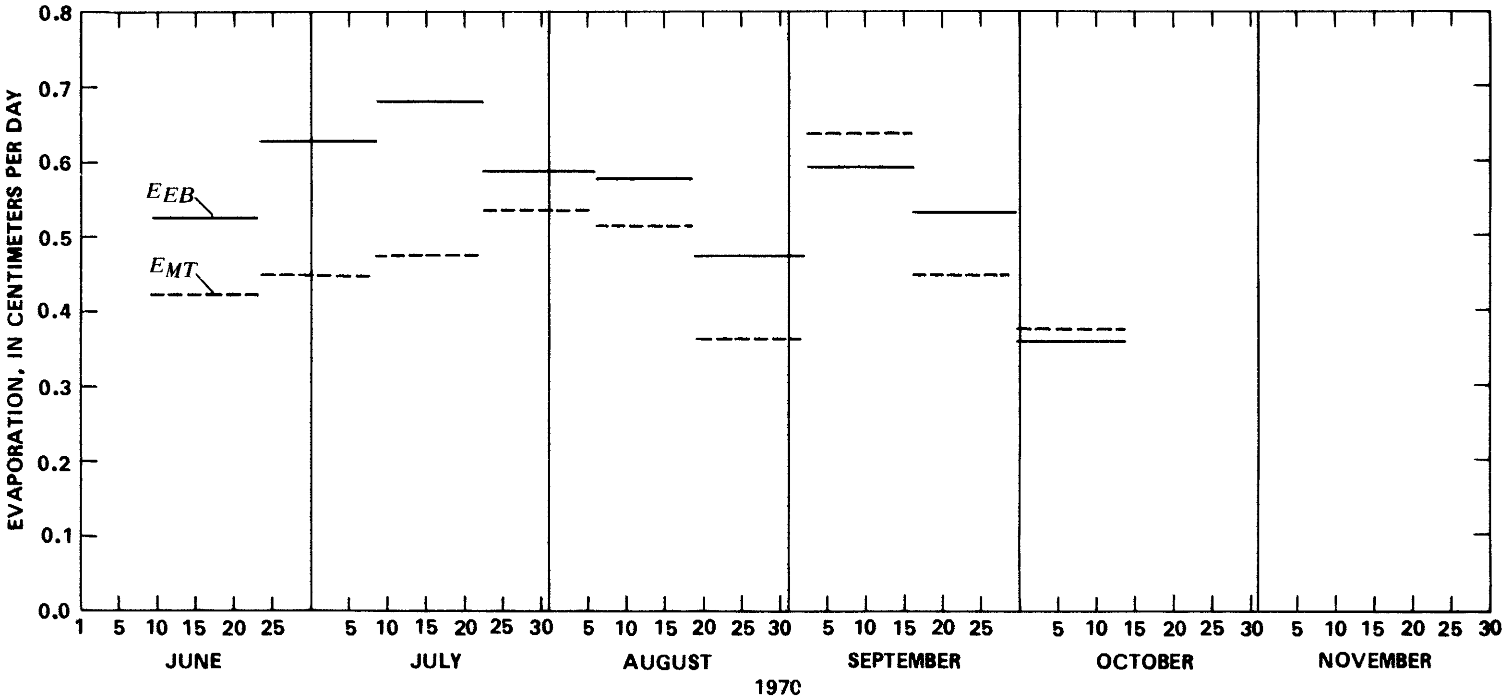

Figure 10.—Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Elevenmile Canyon Reservoir for the 1967–70 record seasons—Continued.

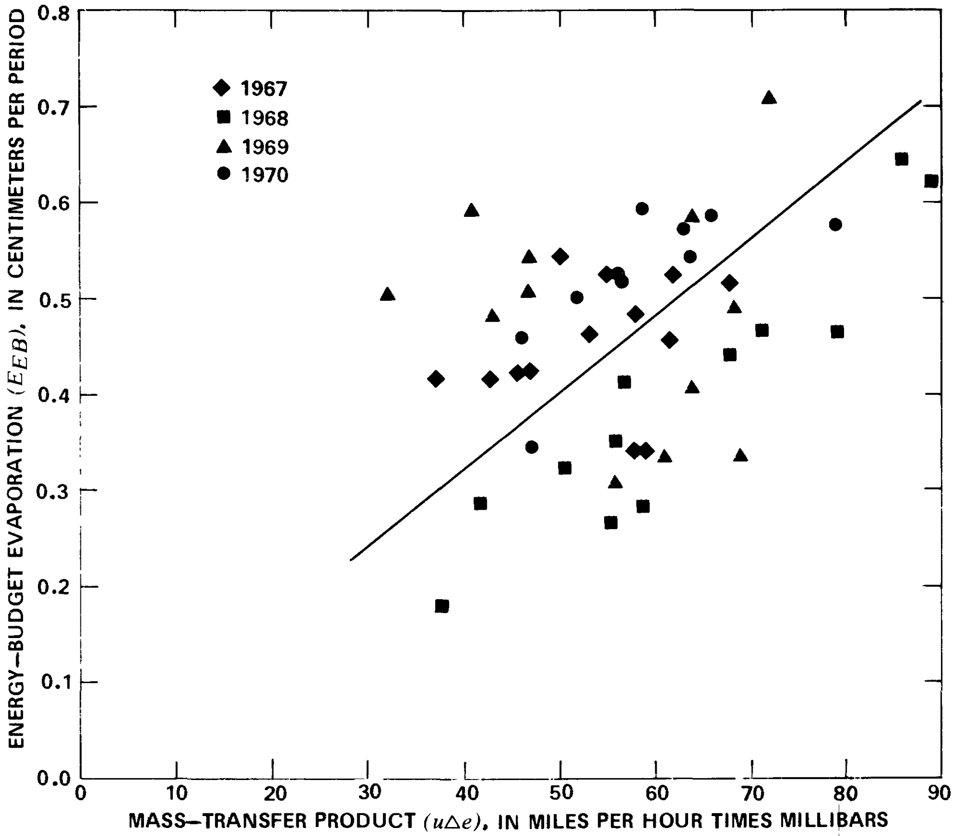

Figure 11.—Calibration plot of the mass–transfer product against evaporation as measured by the energy–budget method at Elevenmile Canyon Reservoir, 1967–70.

For comparison, the value of N for Elevenmile Canyon Reservoir as computed by Harbeck's equation (equation 8 of this report) was found to be 0.00575. This value is considerably smaller than the 0.00800 determined from the calibration against energy-budget values, but still is within the range of expected variations in Harbeck's relationship.

Data.--Evaporation records for Elevenmile Canyon Reservoir as computed by the mass-transfer method for the 7 years of study, 1967-73, are summarized in table 4. Computation periods 1 through 46 for the first 4 years of study are the same as the periods shown in the energy-budget records given in table 3. Computation periods for the last 3 years, 1971-73, generally are 1 week in length, representing the usual period between readings of the dials of the totalizing anemometer (see example, fig. 13). Evaporation hydrographs for the first 4 years of record are shown on figure 10, and figure 14 shows hydrographs for 1971-73.

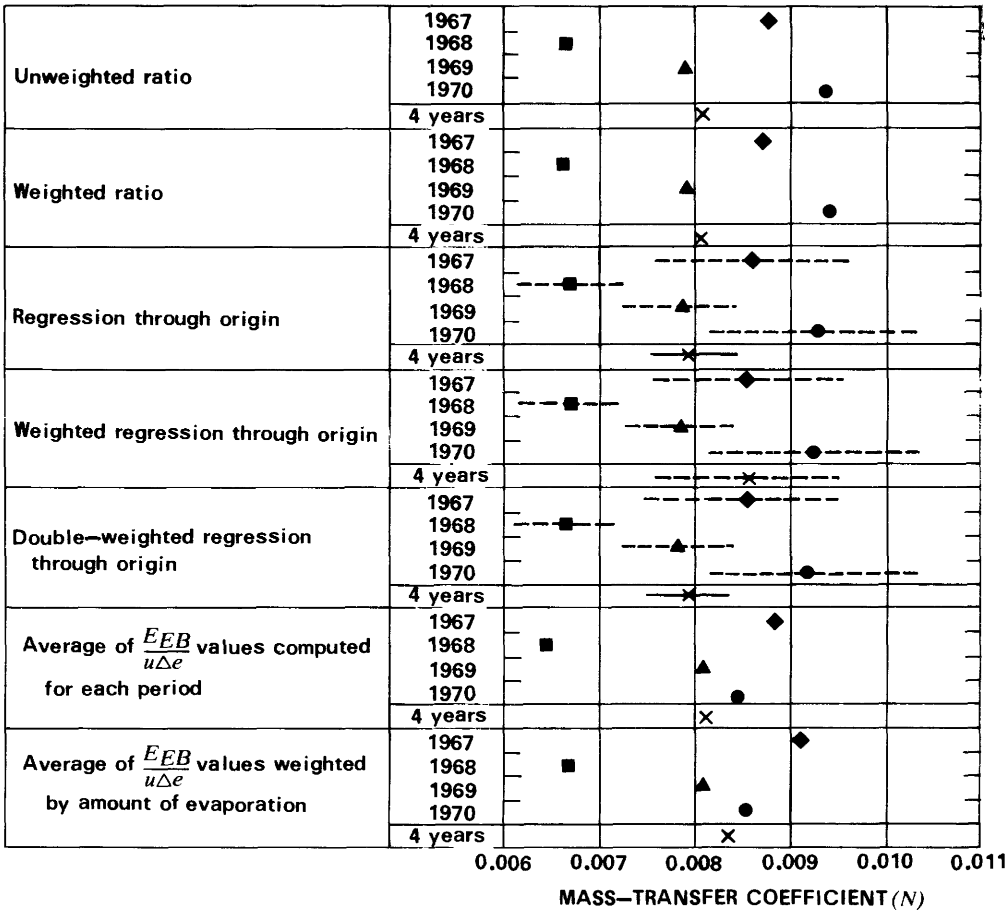

Figure 12.—Mass–transfer coefficients for Elevenmile Canyon Reservoir as determined by different means of calculation from the energy–budget data. Lines through some symbols represent 95–percent confidence limits.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Elevenmile Canyon Reservoir is listed in table 4 with the mass-transfer evaporation.

This evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratio also is listed and, as can be seen, the ratios vary moderately from season to season and are significantly different from the common 0.7 coefficient. The ratios for Elevenmile Canyon Reservoir are fairly uniform and have been calibrated against energy-budget N mass-transfer evaporation.

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1967			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	14	May 3- May 17	8.83	4.9	0.35	4.85	507.5	7.21	0.67
2	14	May 17- May 31	6.15	6.1	.30	4.20	440.0	6.73	.62
3	14	May 31- June 14	6.96	6.6	.37	5.14	541.3	6.88	.75
4	14	June 14- June 28	7.25	7.3	.42	5.93	623.9	7.54	.79
5	12	June 28- July 10	6.19	8.1	.40	4.81	506.6	6.88	.70
6	16	July 10- July 26	5.84	9.5	.44	7.10	749.3	8.20	.87
7	14	July 26- Aug. 9	5.68	11.0	.50	7.00	740.9	8.43	.83
8	14	Aug. 9- Aug. 23	5.85	11.7	.55	7.67	814.1	5.72	1.34
9	14	Aug. 23-Sept. 6	6.16	9.4	.46	6.49	689.6	5.61	1.16
10	14	Sept. 6-Sept. 20	7.35	8.4	.49	6.91	735.5	5.97	1.16
11	14	Sept. 20- Oct. 4	5.92	8.0	.38	5.30	564.2	7.21	.74
12	14	Oct. 4- Oct. 18	7.48	7.8	.47	6.53	694.8	----	----
13	14	Oct. 18- Nov. 1	8.29	7.1	.47	6.59	699.9	----	----
Record season	182	May 3- Nov. 1			0.43	78.52			
Pan season	154	May 3- Oct. 4			0.42	65.40		76.38	0.86

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1968			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
14	5	May 17- May 22	7.00	5.5	0.31	1.54	166.7	----	----
15	14	May 22- June 5	7.34	5.8	.34	4.77	517.2	8.66	0.55
16	14	June 5- June 19	7.54	9.0	.54	7.60	827.1	10.72	.71
17	14	June 19- July 3	7.76	11.2	.70	9.73	1,060.0	11.94	.81
18	14	July 3- July 17	5.73	10.0	.46	6.42	699.0	8.13	.79
19	14	July 17- July 31	5.92	9.5	.45	6.30	686.5	7.59	.83
20	15	July 31- Aug. 15	5.66	9.0	.41	6.11	667.4	6.07	1.01
21	13	Aug. 15- Aug. 28	7.56	11.7	.71	9.20	1,003.0	9.25	.99
22	14	Aug. 28-Sept. 11	6.58	10.9	.57	8.03	875.0	7.11	1.13
23	14	Sept. 11-Sept. 25	7.96	9.2	.59	8.20	893.1	7.16	1.15
24	14	Sept. 25- Oct. 9	7.02	7.6	.43	5.98	650.9	5.41	1.11
25	21	Oct. 9- Oct. 30	7.23	7.1	.41	8.62	939.1	----	----
Record season	166	May 17- Oct. 30			0.50	82.50			
Pan season	140	May 22- Oct. 9			0.52	72.34		82.04	0.88

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

No.	Period: Length (days)	Period: Dates 1969	$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method: Centimeters per day	Reservoir evaporation computed by mass-transfer method: Centimeters per period	Reservoir evaporation computed by mass-transfer method: Acre-feet per period	Pan evaporation: Centimeters per period	Ratio of reservoir to pan evaporation
26	13	May 7- May 20	6.25	6.0	0.30	3.80	428.1	6.83	0.57
27	15	May 20- June 4	6.80	7.1	.39	5.79	631.4	7.98	.73
28	14	June 4- June 18	5.95	7.2	.34	4.80	528.3	7.31	.90
29	14	June 18- July 2	9.20	8.4	.62	8.66	956.1	9.70	.90
30	14	July 2- July 16	5.95	8.8	.42	5.86	648.4	8.55	.69
31	14	July 16- July 30	5.45	9.4	.41	5.74	634.2	7.80	.74
32	14	July 30- Aug. 13	6.10	11.7	.57	7.99	884.8	9.50	.84
33	14	Aug. 13- Aug. 27	5.90	11.2	.53	7.40	818.3	7.39	1.00
34	14	Aug. 27-Sept. 10	5.60	10.7	.48	6.71	741.1	5.79	1.16
35	14	Sept. 10-Sept. 24	5.70	9.2	.42	5.87	648.8	4.11	1.43
36	14	Sept. 24- Oct. 8	6.40	9.4	.48	6.74	744.5	----	----
37	14	Oct. 8- Oct. 22	6.28	7.0	.35	4.92	545.5	----	----
Record season	168	May 7- Oct. 22			0.44	74.28			
Pan season	140	May 7-Sept. 24			0.45	62.62		74.96	0.84

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
38	14	June 10- June 24	8.0	6.6	0.42	5.91	652.1	8.79	0.67
39	14	June 24- July 8	5.8	9.8	.45	6.37	704.5	9.27	.69
40	15	July 8- July 23	5.8	10.3	.48	7.17	793.3	8.89	.81
41	14	July 23- Aug. 6	5.9	11.2	.53	7.40	817.8	8.28	.89
42	13	Aug. 6- Aug. 19	5.5	11.6	.51	6.64	734.1	7.21	.92
43	14	Aug. 19-Sept. 2	5.2	8.9	.37	5.18	573.1	6.07	.85
44	14	Sept. 2-Sept. 16	8.2	9.7	.64	8.91	983.8	7.06	1.26
45	14	Sept. 16-Sept. 30	6.6	8.6	.45	6.36	704.1	4.85	1.31
46	14	Sept. 30- Oct. 14	7.3	6.5	.38	5.31	587.8	3.84	1.38
Record season	126	June 10- Oct. 14			0.47	59.25			
Pan season	126	June 10- Oct. 14			0.47	59.25		64.26	0.92

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
47	6.9	May 26- June 2	7.48	6.6	0.394	2.73	301.6	----	----
48	7.0	June 2- June 9	8.17	7.1	.464	3.24	357.0	5.36	0.60
49	7.1	June 9- June 16	6.27	6.8	.341	2.41	265.7	4.11	.59
50	7.0	June 16- June 23	5.94	6.6	.315	2.21	243.4	4.75	.47
51	7.0	June 23- June 30	6.41	8.6	.441	3.07	328.0	5.66	.54
52	8.0	June 30- July 8	7.20	8.6	.497	3.96	408.2	5.16	.77
53	6.0	July 8- July 14	5.81	9.7	.453	2.73	275.2	3.84	.71
54	7.2	July 14- July 21	6.34	8.1	.410	2.94	292.3	3.96	.74
55	6.8	July 21- July 28	6.11	8.8	.432	2.95	291.9	3.63	.81
56	7.0	July 28- Aug. 4	6.37	10.2	.522	3.65	361.7	3.94	.93

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
57	7.0	Aug. 4- Aug. 11	6.02	9.9	0.477	3.34	330.9	4.06	0.82
58	7.1	Aug. 11- Aug. 18	5.36	8.6	.370	2.64	260.4	3.35	.79
59	6.9	Aug. 18- Aug. 25	6.03	7.9	.379	2.60	254.3	2.54	1.02
60	7.2	Aug. 25-Sept. 1	4.99	8.2	.329	2.36	228.3	3.15	.75
61	7.0	Sept. 1-Sept. 8	8.40	11.1	.749	5.26	497.8	4.04	1.30
62	6.8	Sept. 8-Sept. 15	6.19	11.1	.549	3.75	351.0	4.04	.93
63	7.0	Sept. 15-Sept. 22	7.98	12.0	.766	5.35	498.0	1.19	4.50
64	7.0	Sept. 22-Sept. 29	8.66	9.3	.645	4.51	424.1	3.58	1.26
65	7.0	Sept. 29- Oct. 6	8.41	8.0	.541	3.80	358.6	3.05	1.25
66	6.1	Oct. 6- Oct. 12	5.34	6.5	.276	1.67	158.4	2.36	.71
Record season	139.1	May 26- Oct. 12			0.47	65.17			
Pan season	126	June 2- Oct. 12			0.47	62.44		71.77	0.87

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
67	5.9	May 25- May 31	7.15	5.5	0.313	1.86	179.8	3.91	0.48
68	7.0	May 31- June 7	6.35	6.4	.325	2.27	220.1	6.58	.34
69	7.0	June 7- June 14	5.92	6.6	.311	2.18	217.8	5.74	.38
70	7.2	June 14- June 21	7.72	7.9	.487	3.52	361.4	7.14	.49
71	6.8	June 21- June 28	7.70	10.0	.616	4.17	429.9	8.05	.52
72	7.0	June 28- July 5	8.03	8.7	.561	3.94	406.6	4.60	.86
73	7.0	July 5- July 12	6.62	8.8	.465	3.25	335.8	4.57	.71
74	7.0	July 12- July 19	7.67	9.6	.590	4.12	426.6	5.44	.76
75	7.0	July 19- July 26	6.45	8.9	.461	3.22	335.5	4.88	.66
76	7.0	July 26- Aug. 2	5.71	9.8	.449	3.14	326.8	5.74	.55
77	7.0	Aug. 2- Aug. 9	6.93	9.7	.537	3.76	392.5	4.85	.78

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
78	7.0	Aug. 9- Aug. 16	5.61	8.5	0.383	2.70	281.9	4.83	0.56
79	7.0	Aug. 16- Aug. 23	6.27	8.9	.446	3.11	326.0	3.61	.86
80	7.0	Aug. 23- Aug. 30	5.70	7.8	.356	2.50	262.8	3.00	.83
81	7.0	Aug. 30-Sept. 6	6.81	8.4	.460	3.22	338.8	3.20	1.01
82	7.0	Sept. 6-Sept. 13	6.13	7.8	.384	2.69	281.5	3.40	.79
83	7.0	Sept. 13-Sept. 20	7.14	8.9	.510	3.57	373.7	4.06	.88
84	7.0	Sept. 20-Sept. 27	7.96	10.0	.639	4.47	468.0	4.50	.99
85	7.0	Sept. 27- Oct. 4	7.50	9.0	.542	3.79	396.3	4.32	.88
86	7.0	Oct. 4- Oct. 11	6.77	5.9	.321	2.24	234.5	2.87	.78
87	7.0	Oct. 11- Oct. 18	7.26	6.1	.353	2.48	258.7	2.51	.99
88	7.0	Oct. 18- Oct. 25	5.79	6.5	.300	2.10	219.9	1.54	1.36
Record season	152.9	May 25- Oct. 25			0.45	68.30		99.34	0.69
Pan season	152.9	May 25- Oct. 25			0.45	68.30		99.34	0.69

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
89	7.0	May 30- June 6	6.66	5.6	0.296	2.07	229.3	3.29	0.63
90	6.9	June 6- June 13	5.47	6.4	.280	1.94	216.7	5.39	.36
91	7.1	June 13- June 20	10.58	9.7	.822	5.84	659.9	6.53	.89
92	6.9	June 20- June 27	5.13	7.9	.326	2.25	254.2	5.35	.42
93	7.0	June 27- July 4	5.87	9.3	.435	3.05	345.4	5.85	.52
94	7.0	July 4- July 11	5.72	10.3	.470	3.29	373.0	4.77	.69
95	7.0	July 11- July 18	6.39	7.9	.403	2.82	323.0	3.40	.83
96	7.0	July 18- July 25	5.96	9.2	.437	3.06	352.9	3.89	.79
97	7.0	July 25- Aug. 1	5.55	9.1	.406	2.85	326.2	3.14	.91

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
98	7.0	Aug. 1- Aug. 8	5.81	7.3	0.340	2.37	269.9	3.42	0.69
99	7.0	Aug. 8- Aug. 15	5.66	9.3	.422	2.95	335.0	4.72	.63
100	7.0	Aug. 15- Aug. 22	6.06	8.3	.404	2.82	319.4	5.21	.54
101	7.1	Aug. 22- Aug. 29	6.32	8.5	.431	3.06	345.8	4.04	.76
102	6.9	Aug. 29-Sept. 5	7.22	10.5	.604	4.17	469.7	3.74	1.11
103	7.0	Sept. 5-Sept. 12	6.79	6.9	.376	2.64	296.6	4.02	.66
104	7.0	Sept. 12-Sept. 19	7.67	8.5	.524	3.67	412.2	4.26	.86
105	7.0	Sept. 19-Sept. 26	7.58	9.6	.530	4.06	456.3	4.01	1.01
106	7.0	Sept. 26- Oct. 3	5.58	8.3	.371	2.59	291.4	1.64	1.59

Table 4.--*Summary of mass-transfer terms and pan evaporation for Elevenmile Canyon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
107	7.0	Oct. 3- Oct. 10	7.83	7.6	0.475	3.32	372.8	2.56	1.30
108	7.0	Oct. 10- Oct. 17	6.80	6.1	.334	2.36	264.3	1.93	1.22
109	6.0	Oct. 17- Oct. 23	4.64	6.0	.222	1.33	149.5	2.94	.45
110	8.0	Oct. 23- Oct. 31	3.74	5.9	.177	1.41	158.3	2.70	.52
111	7.0	Oct. 31- Nov. 7	6.11	5.3	.260	1.82	203.6	----	----
112	7.0	Nov. 7- Nov. 14	3.22	3.7	.096	.674	75.40	----	----
113	7.0	Nov. 14- Nov. 21	4.89	4.8	.189	1.32	147.6	----	----
114	7.0	Nov. 21- Nov. 28	3.89	4.0	.126	.880	98.37	----	----
115	9.0	Nov. 28- Dec. 7	3.54	2.6	.074	.666	74.47	----	----
Record season	190.9	May 30- Dec. 7			0.36	69.28			
Pan season	153.9	May 30- Oct. 31			0.42	63.92		86.80	0.74

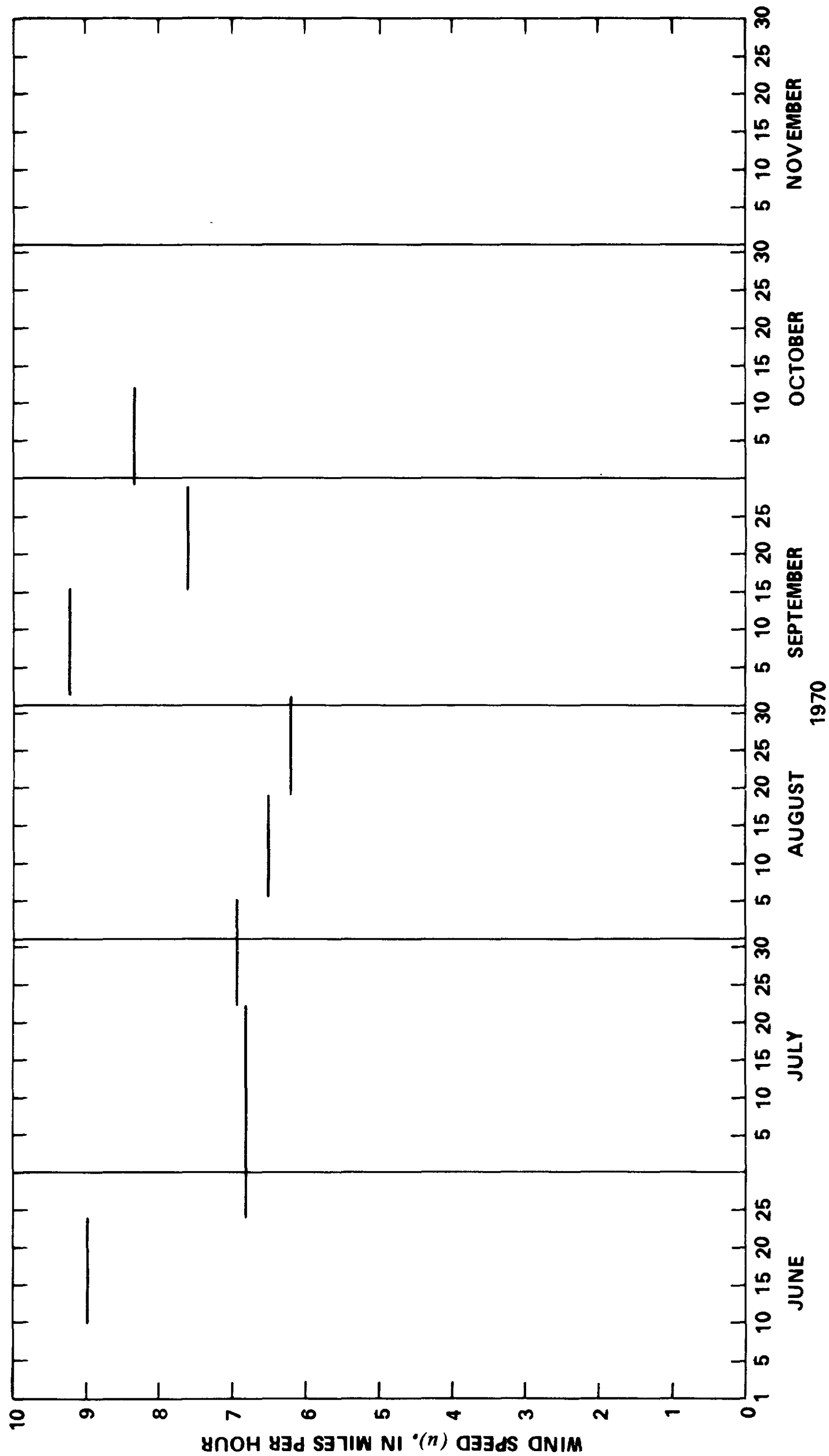

Figure 13.--Time graph of wind speeds, u, at Elevenmile Canyon Reservoir.

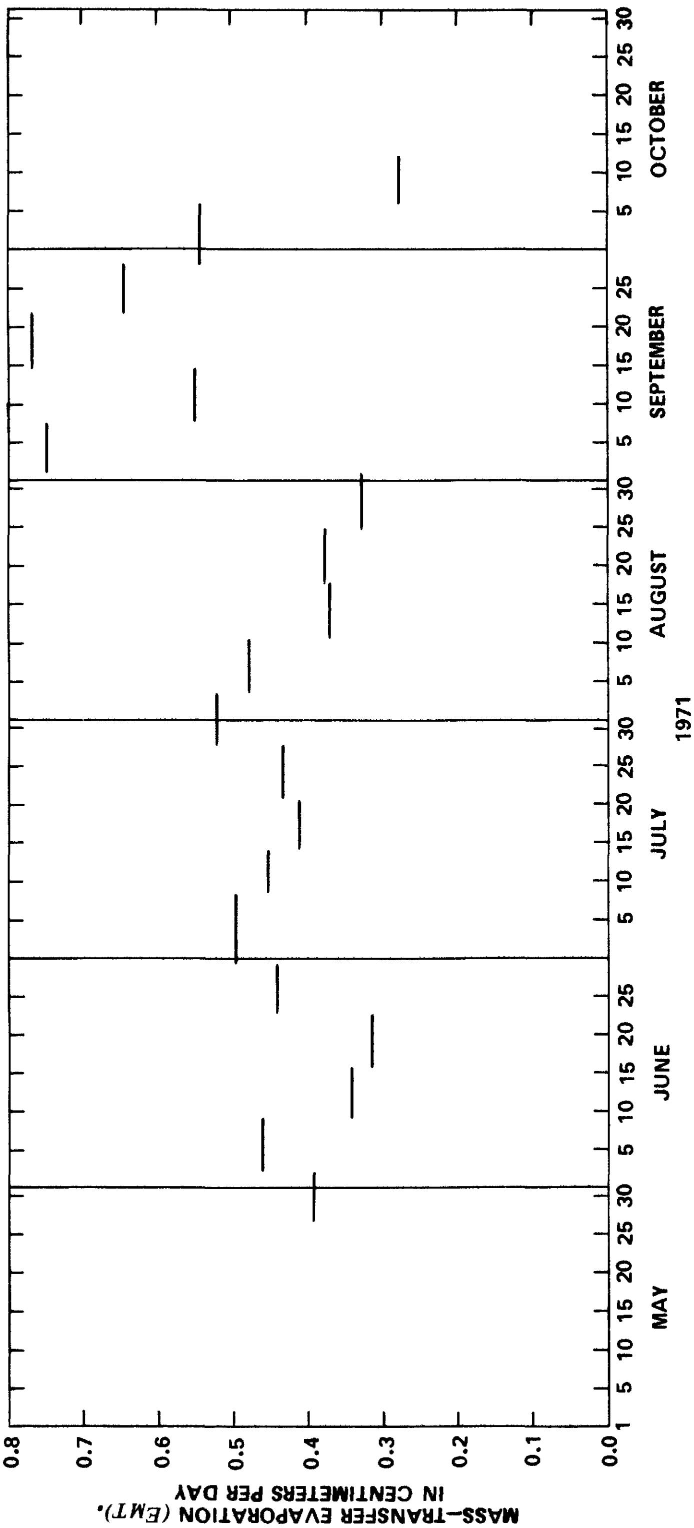

Figure 14.—Rates of mass-transfer evaporation, E_{MT}, from Elevenmile Canyon Reservoir for the 1971–73 record seasons.

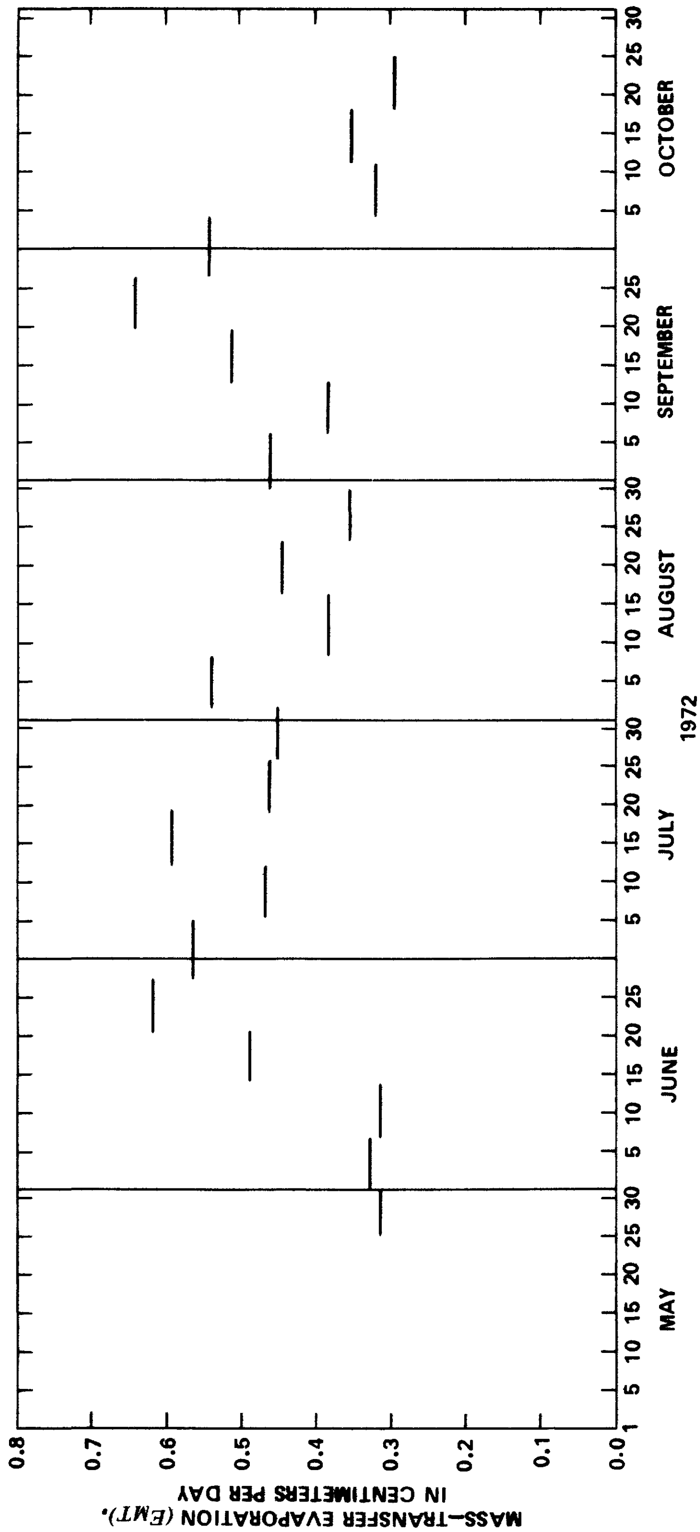

Figure 14.—Rates of mass-transfer evaporation, E_{MT}, from Elevenmile Canyon Reservoir for the 1971–73 record seasons—Continued.

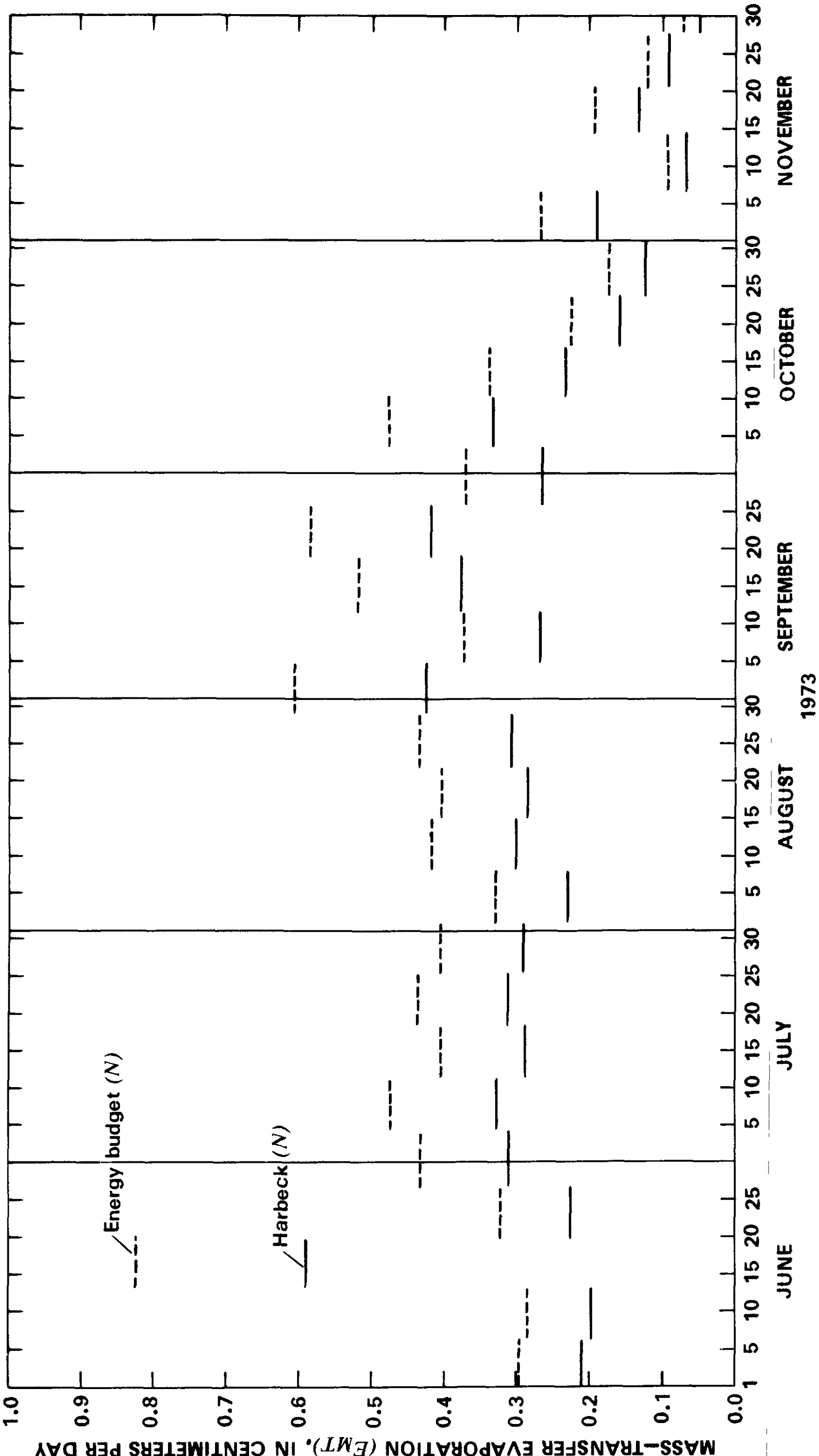

Figure 14.—Rates of mass-transfer evaporation, E_{MT}, from Elevenmile Canyon Reservoir for the 1971–73 record seasons—Continued.

Corrections to pan evaporation for advected energy, based on equation 11, are listed in table 5. These corrections have very little meaning for Elevenmile Canyon Reservoir because of the high flow-through and rapid changes in storage. Discrepancies resulted from averaging of data between thermal surveys, as computed in equation 10. These corrections are not applicable to reservoirs with short detention times or those experiencing rapid changes in volume.

Table 5.--*Advection and storage corrections for pan-based evaporation data for Elevenmile Canyon Reservoir*

Period			Q_v	Q_w	Q_x		Evaporation effect, ΔE	
No.	Length (days)	Dates 1967	Cal cm^{-2}	d^{-1}		α	Centimeters per day	Centimeters per period
1	14	May 3- May 17	1	3	139	0.42	-0.100	-1.40
2	14	May 17- May 31	9	5	111	.43	- .078	-1.09
3	14	May 31- June 14	6	5	113	.45	- .086	-1.20
4	14	June 14- June 28	7	7	125	.48	- .102	-1.43
5	12	June 28- July 10	14	9	147	.50	- .121	-1.45
6	16	July 10- July 26	18	10	71	.51	- .055	- .88
7	14	July 26- Aug. 9	13	11	21	.52	- .017	- .24
8	14	Aug. 9- Aug. 23	10	10	-118	.51	- .103	-1.44
9	14	Aug. 23-Sept. 6	4	8	- 40	.50	.031	.43
10	14	Sept. 6-Sept. 20	- 5	7	-101	.49	.074	1.04
11	14	Sept. 20- Oct. 4	1	6	- 37	.45	.020	.28
12	14	Oct. 4- Oct. 18	1	4	-136	.46	.104	1.45
13	14	Oct. 18- Nov. 1	- 2	3	-188	.42	.130	1.82
Record season	182	May 3- Nov. 1						-4.11

Table 5.--*Advection and storage corrections for pan-based evaporation data for Elevenmile Canyon Reservoir*--Continued

Period			Q_v	Q_w	Q_x		Evaporation effect, ΔE	
No.	Length (days)	Dates 1968	Cal cm^{-2} d^{-1}			α	Centimeters per day	Centimeters per period
14	5	May 17- May 22	2	2	311	0.41	-0.215	-1.08
15	14	May 22- June 5	6	3	255	.42	- .179	-2.51
16	14	June 5- June 19	10	6	168	.47	.131	-1.83
17	14	June 19- July 3	15	11	81	.52	- .068	- .96
18	14	July 3- July 17	16	7	107	.50	- .099	-1.38
19	14	July 17- July 31	12	7	15	.51	- .010	- .12
20	15	July 31- Aug. 15	18	6	9	.50	.003	.04
21	13	Aug. 15- Aug. 28	0	11	- 62	.50	.043	.56
22	14	Aug. 28-Sept. 11	- 3	6	- 87	.50	.066	.93
23	14	Sept. 11-Sept. 25	1	7	-121	.49	.010	.13
24	14	Sept. 25- Oct. 9	0	4	- 97	.44	.069	.97
25	21	Oct. 9- Oct. 30	- 1	3	-141	.43	.010	2.09
Record season	166	May 17- Oct. 30						-3.16
Period			Q_v	Q_w	Q_x		Evaporation effect, ΔE	
No.	Length (days)	Dates 1969	Cal cm^{-2} d^{-1}			α	Centimeters per day	Centimeters per period
26	13	May 7- May 20	2	4	172	0.42	-0.123	-1.60
27	15	May 20- June 4	13	5	115	.44	- .080	-1.20
28	14	June 4- June 18	24	5	7	.48	.010	.14
29	14	June 18- July 2	7	8	119	.51	- .102	-1.43
30	14	July 2- July 16	18	7	128	.50	- .010	-1.39
31	14	July 16- July 30	26	9	88	.50	- .060	- .84
32	14	July 30- Aug. 13	17	11	48	.53	- .038	- .53
33	14	Aug. 13- Aug. 27	12	10	- 39	.52	.036	.51
34	14	Aug. 27-Sept. 10	1	8	- 79	.51	.063	.88
35	14	Sept. 10-Sept. 24	- 4	6	-129	.49	.099	1.39
36	14	Sept. 24- Oct. 8	- 2	5	-200	.48	.157	2.20
37	14	Oct. 8- Oct. 22	-13	3	-284	.41	.186	2.60
Record season	168	May 7- Oct. 22						0.73

Table 5.--*Advection and storage corrections for pan-based evaporation data for Elevenmile Canyon Reservoir*--Continued

Period			Q_v	Q_w	Q_x	α	Evaporation effect, ΔE	
No.	Length (days)	Dates 1970	Cal cm^{-2} d^{-1}				Centimeters per day	Centimeters per period
38	14	June 10- June 24	47	7	173	0.48	-0.108	-1.51
39	14	June 24- July 8	39	11	154	.50	- .107	-1.50
40	15	July 8- July 23	52	12	40	.52	.000	.00
41	14	July 23- Aug. 6	35	11	57	.51	- .029	- .40
42	13	Aug. 6- Aug. 19	27	11	6	.51	.009	.11
43	14	Aug. 19-Sept. 2	10	9	- 37	.49	.032	.44
44	14	Sept. 2-Sept. 16	6	10	-175	.50	.145	2.04
45	14	Sept. 16-Sept. 30	8	7	-173	.46	.294	4.12
46	14	Sept. 30- Oct. 14	- 8	4	-170	.45	.120	1.69
Record season	126	June 10- Oct. 14						5.35

EVAPORATION FROM DILLON RESERVOIR

Dillon Reservoir has a spillway elevation of 9,017 ft (2,748.4 m) and discharges to the Blue River, flowing generally north. The reservoir supplies water to the Denver Board of Water Commissioners' system through the Harold D. Roberts Tunnel across the Continental Divide into the South Platte River system near Grant, Colo. The reservoir is in a basin and is generally oriented north-south, while the prevailing wind is generally from the west. The major tributaries are Tenmile Creek, and the Blue and the Snake Rivers. The reservoir has a drainage area of 335 mi^2 (868 km^2). The active storage capacity is 254,036 acre-ft (313 hm^3) with surface area of 3,222 acres (13.0 km^2), mean depth of 78.8 ft (24 m), and maximum depth of 188 ft (57.3 m). The dam was completed in 1963 for the purpose of supplying water to the Denver Board of Water Commissioners' system through the Harold D. Roberts Tunnel.

Evaporation studies of Dillon Reservoir were begun in 1969. Energy-budget studies were conducted for 3 years, 1969-71. Evaporation measurement by the mass-transfer method and by standard class-A pan were conducted for 5 years, 1969-73.

Data for energy-budget computation, including air temperature (wet bulb and dry bulb) and radiation, were measured with instruments located within 150 ft (46 m) of the caretaker's house east of the reservoir. Measurements of air temperature, relative humidity, and pan evaporation used in mass-transfer and pan studies were made at instruments also located within 150 ft (46 m) of the caretaker's house. Temperatures of the reservoir surface and average wind speed were measured by instruments attached to a raft anchored near the center of the reservoir.

Energy-Budget Parameters

Data for solar radiation (Q_s) are from a pyranometer installed at the caretaker's house on the east side of the reservoir. Short periods of missing pyranometer data were filled in by estimates based upon tabulated values of clear sky radiation and observed cloud cover. A time graph of solar-radiation (Q_s) values recorded at Dillon Reservoir during 1971 is shown on figure 15. The values are based upon daily integrator readings from the recorder. Records of wet-bulb and dry-bulb temperatures were computed largely from the integrator records of the recorder connected to the thermocouple psychrometer described earlier. Except for minor difficulties caused by broken thermocouple leads, the records were quite complete. It was difficult to evaluate the effect of freezing upon the wet-bulb temperature record. Consequently, most vapor-pressure records for periods of psychrometer reservoir freezing were estimated from hygrothermograph records at the reservoir. As indicated by the vapor-pressure records, the values of air vapor pressure (e_a) were recorded daily (fig. 16) and then averaged over the number of days between thermal surveys for computation of evaporation. Errors could be expected to result from this type of computation because the relationship between temperature and vapor pressure is not linear. On the other hand, the errors are small and the cost of additional accuracy afforded by more frequent thermal surveys could not be justified.

Values of saturation vapor pressure at the temperature of the water surface (e_o) were selected from tables of the saturation vapor pressure of water, as functions of daily mean temperature (T_o) (fig. 17) computed from records of the thermograph or thermistor on the raft in the center of the lake. Record of e_o for 1971 is shown on figure 16.

Temperature-survey data were used to compute the mean temperature in each layer of the reservoir. The energy in each layer, measured above a base of 0°C, was computed as the product of temperature and the volume of the layer. Finally, average storage, in calories per square centimeter, was computed as the sum of the individual layers divided by the surface area of the reservoir. Changes in stored energy between any two surveys, divided by the length of the period, yielded the term Q_x, in calories per square centimeter per day (see equation 10).

Volumes used in the computation of energy storage were computed from a capacity table supplied by the Denver Board of Water Commissioners. Computation of evaporation would not be affected by errors in the capacity table during those periods when there is little or no change in heat storage. The greatest error would be expected during periods of rapid heating during the spring and early summer.

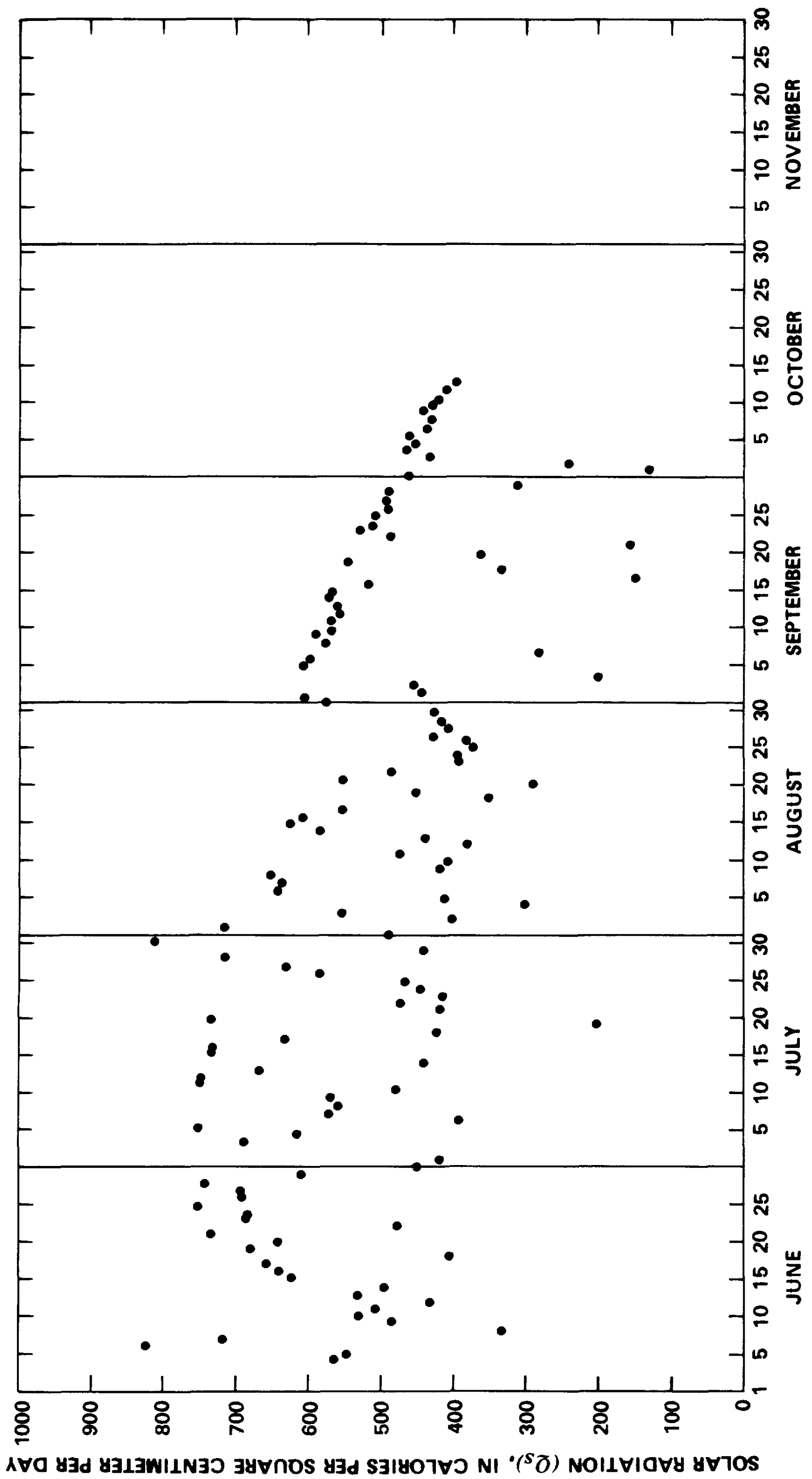

Figure 15.—Time graph of solar radiation, Q_S, measured at Dillon Reservoir.

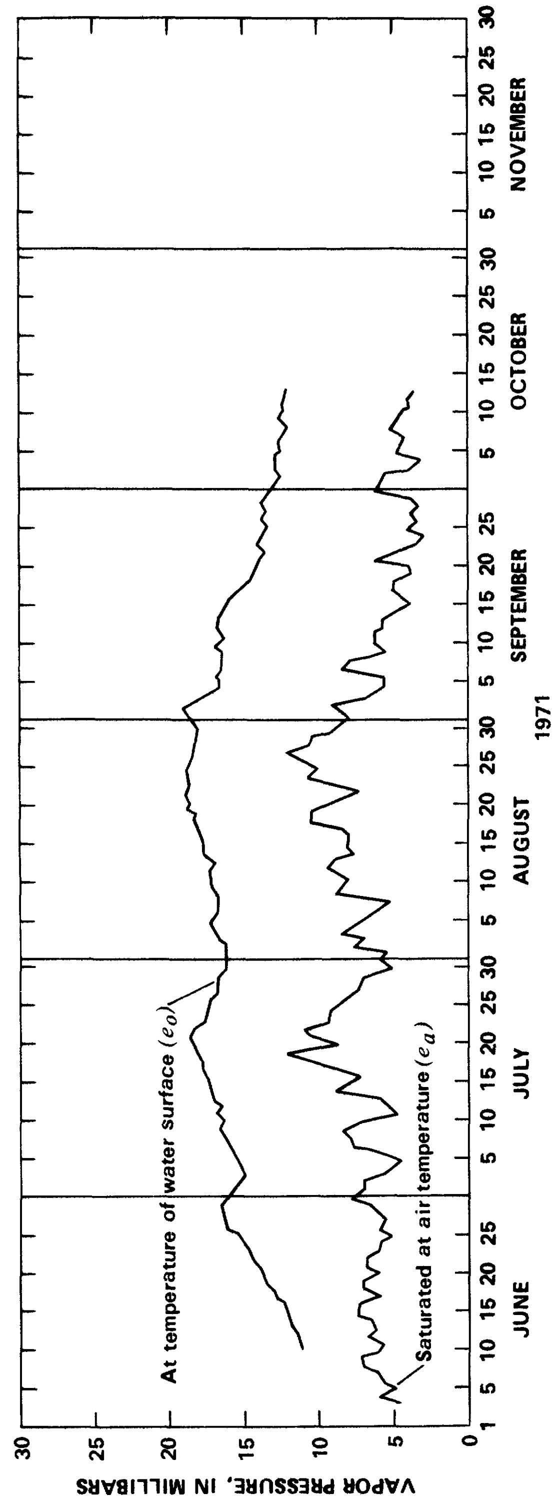

Figure 16.--Time graph of vapor pressures, e_o and e_a, at Dillon Reservoir.

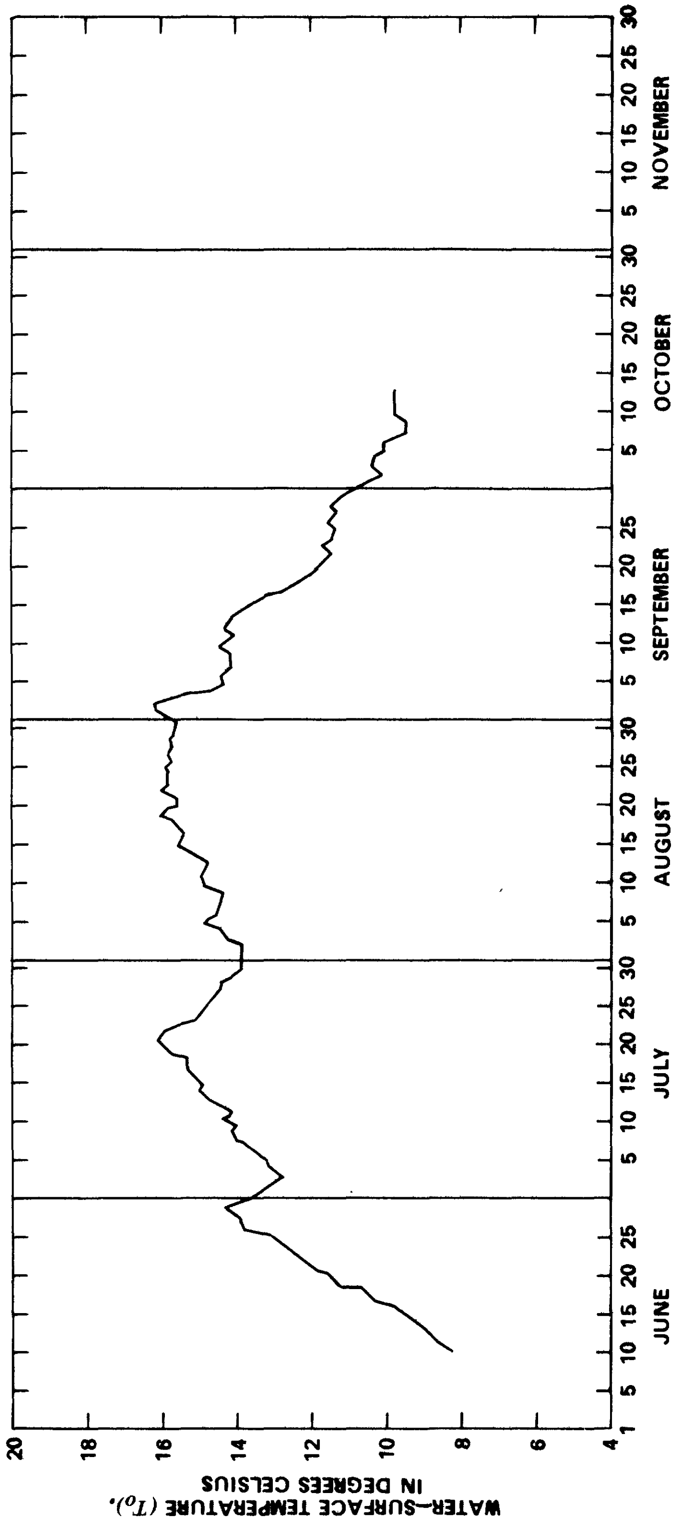

Figure 17.--Time graph of water-surface temperature, T_0, of Dillon Reservoir.

It is obvious that reliable values of Q_x can be computed only between two accurate measurements of energy storage. Consequently, solutions of the energy-budget formula are limited to those periods between major temperature surveys.

Volume and temperature records for rainfall, inflow, and outflow were used to compute advected energy (Q_v). Advected energy is a relatively small term in the energy budgets of reservoirs having large ratios of volume/flow-through.

In reporting values of Q_v, it sometimes is convenient to combine the Q_v data with data on changes in energy storage (Q_x), and to report the difference (Q_v-Q_x). The combination Q_v-Q_x represents the combined last two terms of the numerator in equation 6. Values of Q_v-Q_x for Dillon Reservoir for the 1971 record season are shown in figure 18.

Energy-Budget Records

Energy-budget records for Dillon Reservoir for 1969-71 are summarized in table 6. Evaporation rates for the period also are shown graphically by the evaporation hydrographs on figure 19. Data are summarized according to periods between thermal surveys. Most of these periods were 14 days long, but length ranged from 13 to 15 days.

Evaporation rates during the computation periods ranged from 0.239 to 0.592 cm/d. Seasonal average rates for the periods of record ranged from the low of 0.408 cm/d for 1971 to the high of 0.442 cm/d for 1970. The average rate for 1969 is 0.439 cm/d and is very close to the value for 1971. Average rates for the different record seasons are directly comparable because of similarities in the dates of the record periods from year to year.

Mass-Transfer Records

Calibration of the coefficient.--Data from the energy-budget studies of 1969-71 were used to calibrate the mass-transfer coefficient, N, used in equation 7, for Dillon Reservoir. Values of evaporation rates measured by the energy budget, E_{EB}, plotted against the mass-transfer product $u_2(e_o-e_a)$ are shown on figure 20. The slope of the relation line defined by the plot on figure 20 will be equal to the value of N.

Several different methods were used to determine the value of N from the data defined on figure 20. The values, as determined by different methods, are summarized on figure 21, where the ratio technique refers to the slope of a line passing through the origin and through the means of the two variables of figure 2, E_{EB} and $u_2(e_o-e_a)$. Weighted ratios were computed considering the lengths of the periods, and obviously are very nearly the same as the unweighted ratios. Results of unweighted, weighted, and double-weighted regressions

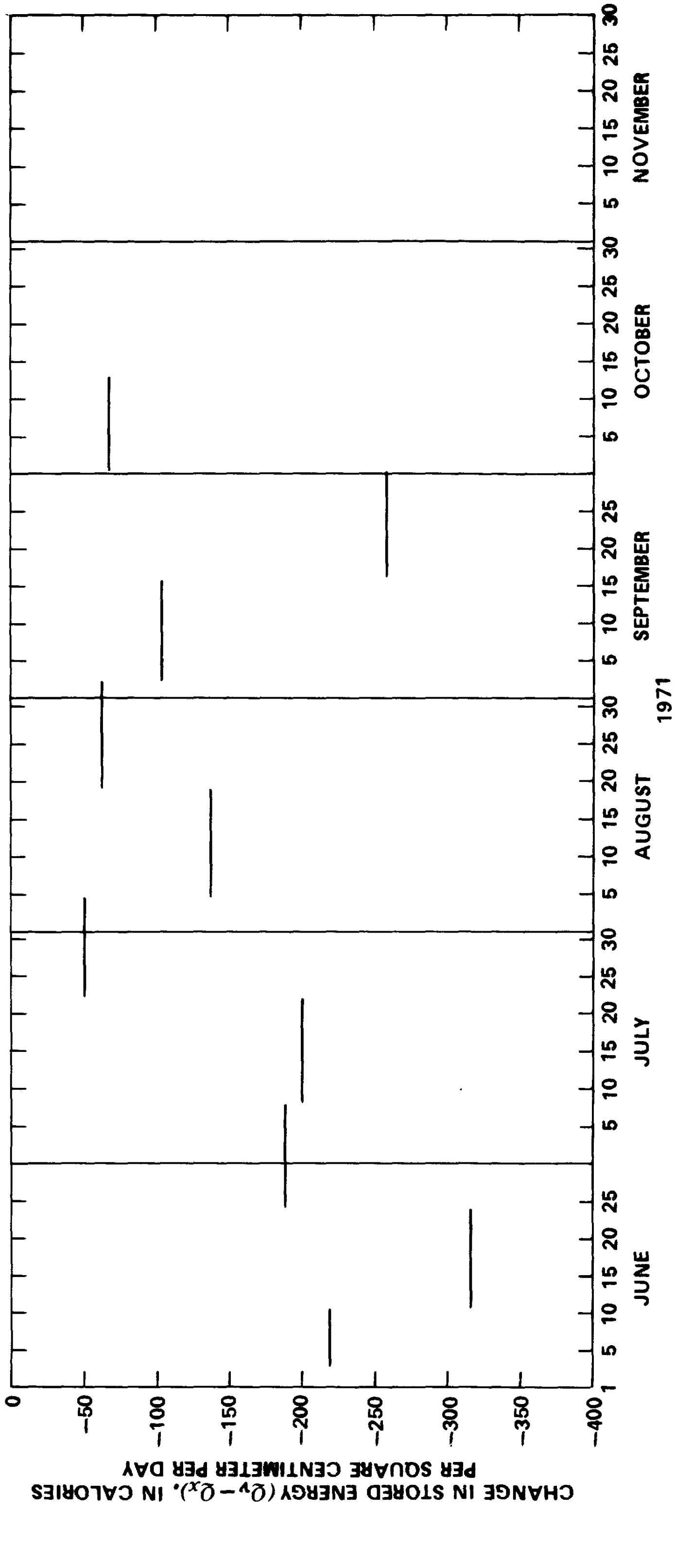

Figure 18.—Time graph of advected energy minus changes in stored energy, $Q_v - Q_x$, for Dillon Reservoir.

Table 6.--*Summary of energy-budget terms and evaporation computation for Dillon Reservoir*

No.	Length (days)	Dates 1969	Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation: Centimeters per day	Evaporation: Centimeters per period
			Cal cm^{-2} d^{-1}											
1	14	May 22- June 5	656	42	661	717	94	452	220	-25	3	-0.112	0.372	5.24
2	14	June 5- June 19	426	31	650	741	-27	57	177	39	3	.221	.300	4.20
3	14	June 19- July 3	589	31	719	740	-78	164	274	9	5	.032	.465	6.51
4	14	July 3- July 17	566	36	704	770	-59	151	254	- 6	6	- .022	.430	6.02
5	14	July 17- July 31	504	34	727	796	-12	93	270	18	7	.067	.460	6.44
6	14	July 31- Aug. 14	580	37	727	807	5	92	348	17	10	.050	.592	8.29
7	14	Aug. 14- Aug. 28	510	34	683	807	6	- 23	321	51	9	.158	.546	7.64
8	14	Aug. 28-Sept. 11	441	32	669	796	10	- 48	276	56	8	.202	.470	6.58
9	14	Sept. 11-Sept. 25	396	30	602	780	7	- 87	212	65	5	.306	.360	5.04
10	14	Sept. 25- Oct. 9	385	29	567	760	1	-240	299	99	7	.330	.506	7.08
11	15	Oct. 9- Oct. 24	293	25	522	717	- 6	-251	197	119	3	.603	.332	4.98
Record season	155	May 22- Oct. 24	----	----	----	----	----	----	----	----	----	----	0.439	68.02

Table 6.--*Summary of energy-budget terms and evaporation computation for Dillon Reservoir*--Continued

Period			Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio	Evaporation	
No.	Length (days)	Dates 1970	Cal cm^{-2} d^{-1}									R	Centimeters per day	Centimeters per period
12	14	May 28- June 11	611	38	624	697	-11	313	169	5	2	0.029	0.285	3.99
13	14	June 11- June 25	665	43	673	730	76	383	267	-14	5	- .052	.451	6.31
14	14	June 25- July 9	626	38	693	773	85	304	279	3	7	.011	.474	6.64
15	14	July 9- July 23	602	37	711	791	-77	84	287	29	8	.102	.488	6.83
16	13	July 23- Aug. 5	590	37	717	801	-50	60	313	37	9	.118	.532	6.92
17	15	Aug. 5- Aug. 20	456	32	769	803	-32	29	279	42	8	.152	.474	7.11
18	14	Aug. 20-Sept. 3	406	30	695	791	-12	-24	247	39	7	.157	.419	5.87
19	14	Sept. 3-Sept. 17	468	33	646	775	- 3	-59	287	68	7	.236	.487	6.82
20	14	Sept. 17- Oct. 1	488	37	550	756	-26	-122	248	88	5	.354	.420	5.88
21	14	Oct. 1- Oct. 15	436	35	472	735	-24	-224	230	104	4	.454	.389	5.45
Record season	140	May 28- Oct. 15	---	---	---	---	---	---	---	---	---	---	0.442	61.82

Table 6.--*Summary of energy-budget terms and evaporation computation for Dillon Reservoir*--Continued

Period			Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation	
No.	Length (days)	Dates 1971	Cal cm^{-2} d^{-1}										Centi-meters per day	Centi-meters per period
22	7	June 3- June 10	570	39	586	706	30	250	173	16	2	0.091	0.292	2.06
23	14	June 10- June 24	572	40	638	731	52	367	141	-20	2	- .141	.239	3.35
24	14	June 24- July 8	610	41	646	764	-171	16	263	- 4	6	- .017	.445	6.23
25	14	July 8- July 22	576	39	693	780	-80	117	250	- 3	6	- .011	.424	5.94
26	14	July 22- Aug. 5	527	38	660	776	-43	7	286	30	7	.105	.485	6.79
27	14	Aug. 5- Aug. 19	510	37	685	780	-20	118	214	21	5	.098	.363	5.08
28	14	Aug. 19-Sept. 2	440	35	685	790	-10	53	201	30	5	.148	.342	4.79
29	14	Sept. 2-Sept. 16	505	37	595	775	5	-97	318	64	8	.201	.540	7.56
30	14	Sept. 16-Sept. 30	417	33	551	747	4	-252	331	106	7	.321	.560	7.84
31	14	Sept. 30- Oct. 14	402	33	548	728	1	-66	195	57	3	.292	.330	4.62
Record season	133	June 3- Oct. 14	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	0.408	54.26

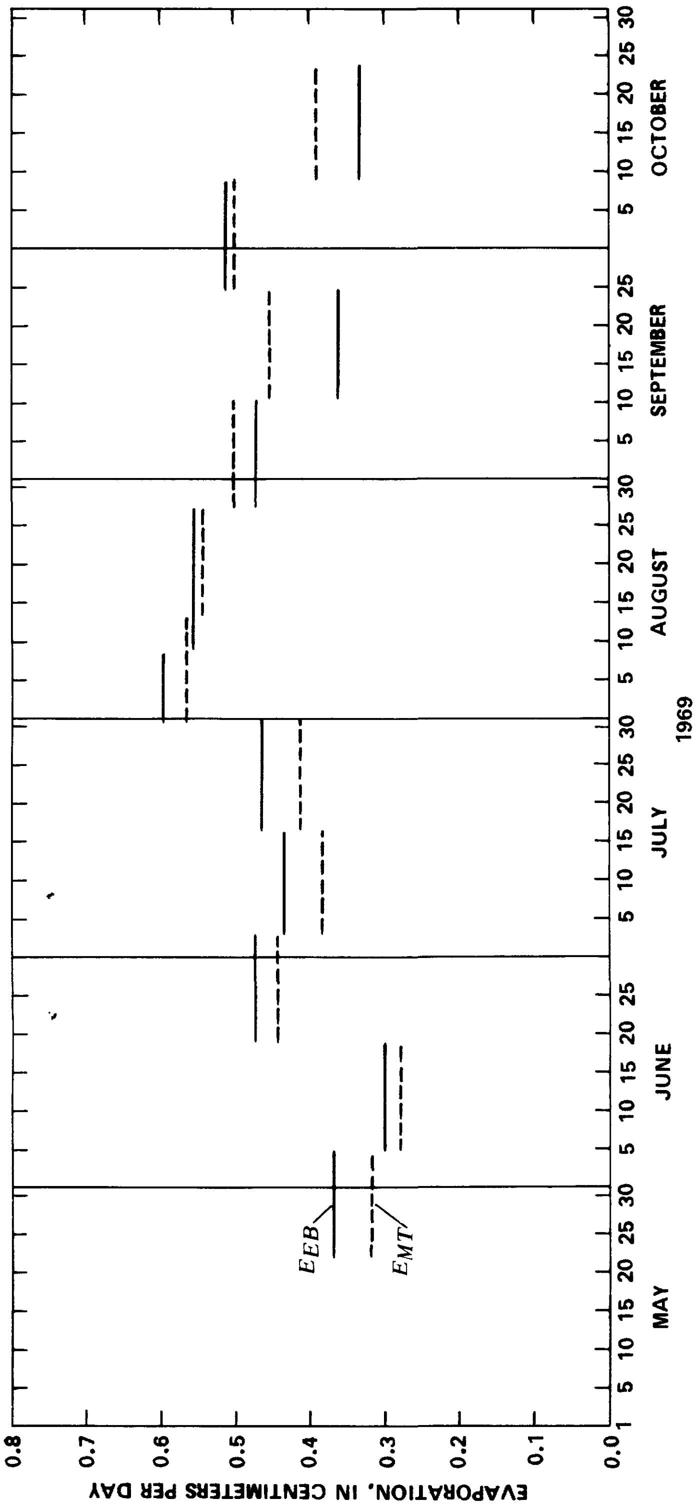

Figure 19.--Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Dillon Reservoir for the 1969-71 record seasons.

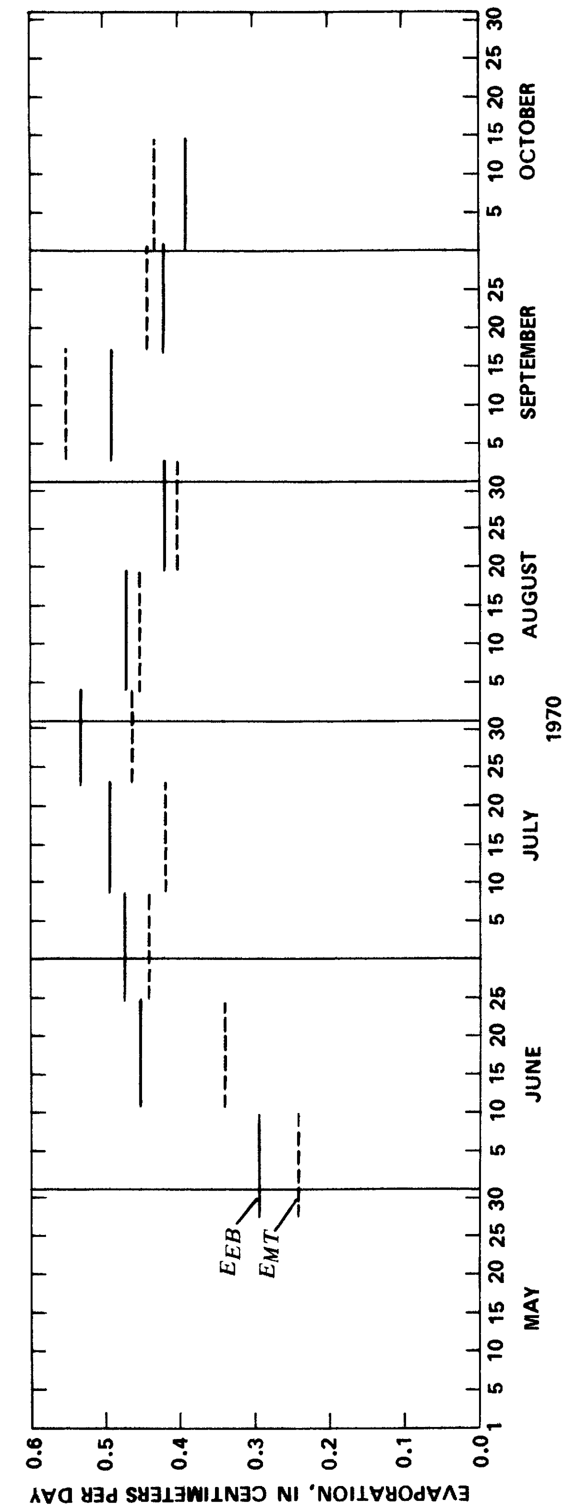

Figure 19.--Rates of energy-budget, E_{EB}, and mass-transfer, E_{MT}, evaporation from Dillon Reservoir for the 1969-71 record seasons--Continued.

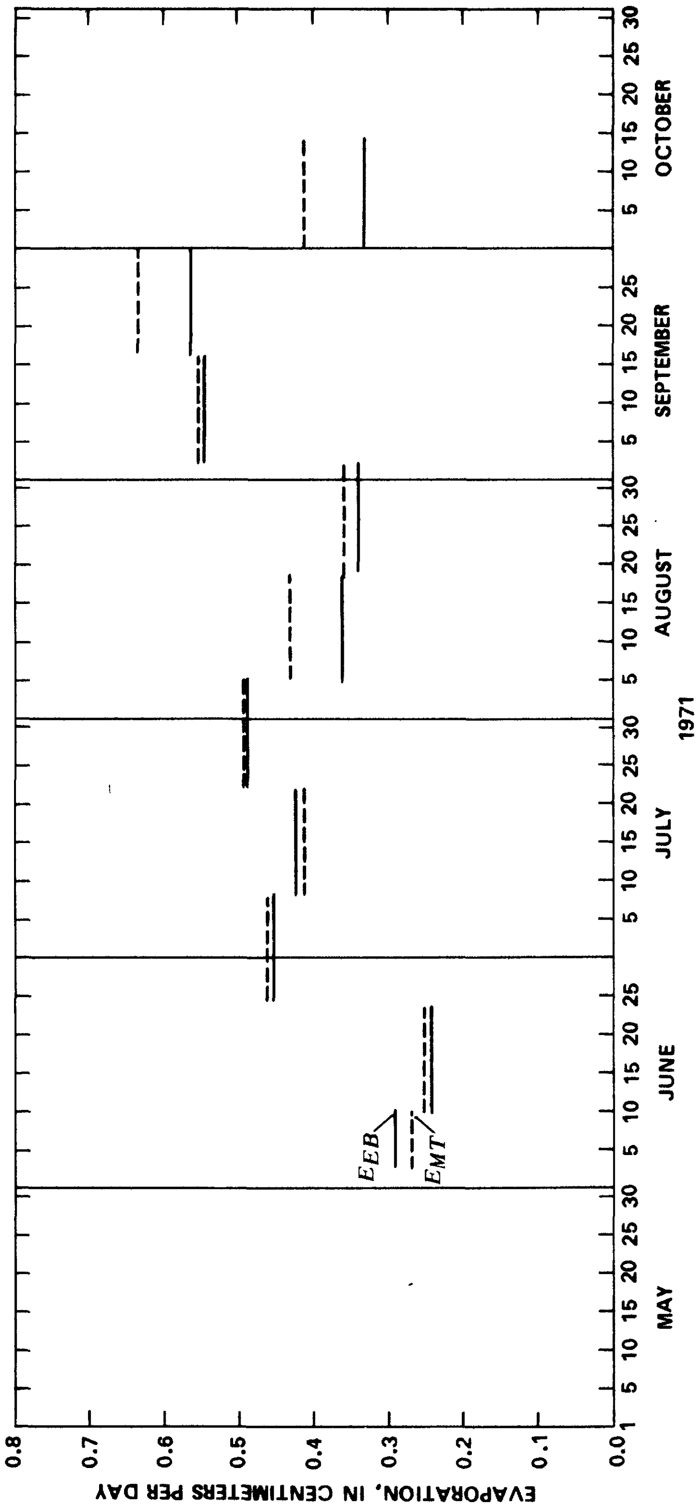

Figure 19.—Rates of energy–budget, E_{EB}, and mass–transfer, E_{MT}, evaporation from Dillon Reservoir for the 1969–71 record seasons—Continued.

also are summarized on figure 21. Dashed horizontal lines in the figure represent 95-percent confidence limits for the regression coefficients.

Based upon the results shown on figure 21, a value of N of 0.00796 was selected for Dillon Reservoir. However, the plot shows that 1971 data defined an N value about 6 percent less than the mean, and 1970 data showed a value about 6 percent greater than the mean. Different annual patterns also seem to be indicated by the patterns of the data as they are plotted on figure 20 for 1970, as compared to 1969 and 1971, due to a period of low evaporation during August.

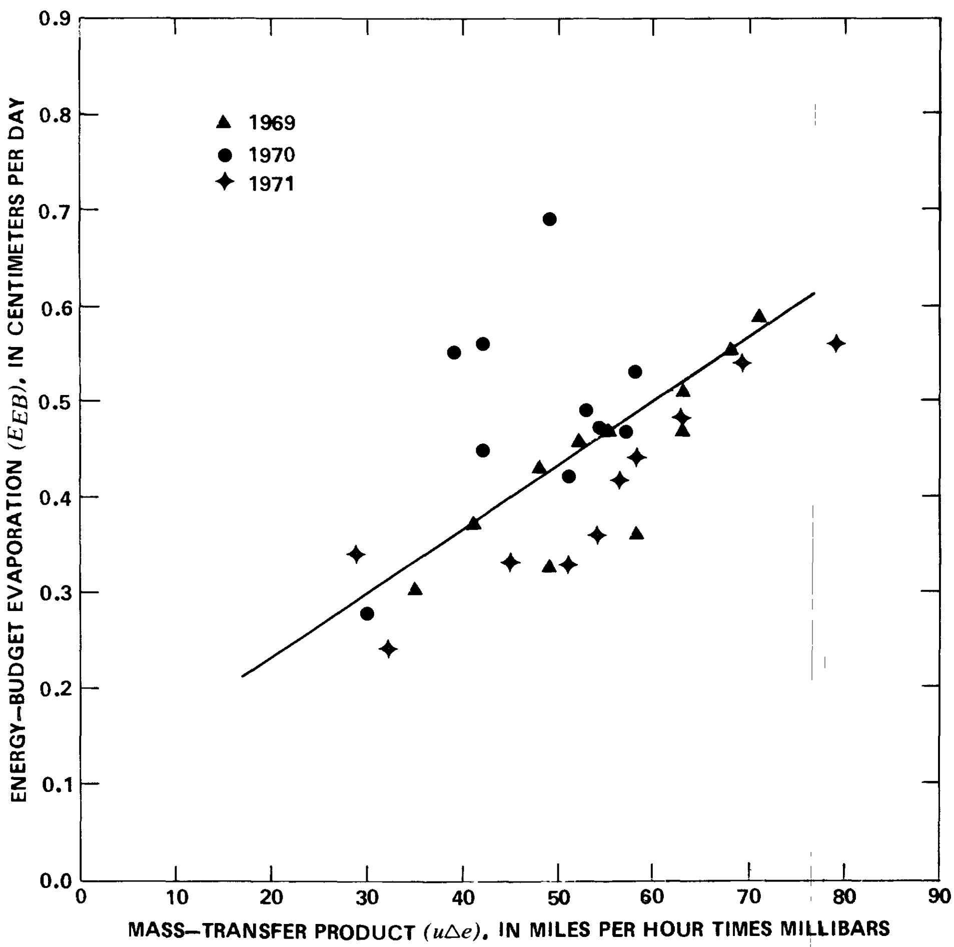

Figure 20.––Calibration plot of the mass–transfer product against evaporation as measured by the energy–budget method at Dillon Reservoir.

For comparison, the value of *N* for Dillon Reservoir as computed by Harbeck's equation (equation 8 of this report) was found to be 0.00577. This value is considerably smaller than the 0.00796 determined from the calibration against energy-budget values, but still is within the range of expected variations in Harbeck's relationship.

Data.--Evaporation records for Dillon Reservoir as computed by the mass-transfer method for the 5 years of study, 1969-73, are summarized in table 7. Computation periods for the first 3 years of study, 1969-71, are the same as the periods shown in the energy-budget records given in table 5. Examples of the records of wind speeds, averaged over the 2-week periods of 1971, are given in figure 22. Computation periods for the last 2 years, 1972-73, generally are 1 week in length, representing the usual period between readings of the dials of the totalizing anemometer. Evaporation hydrographs for the first 3 years of record are shown on figure 19, and hydrographs for 1972-73 are shown on figure 23.

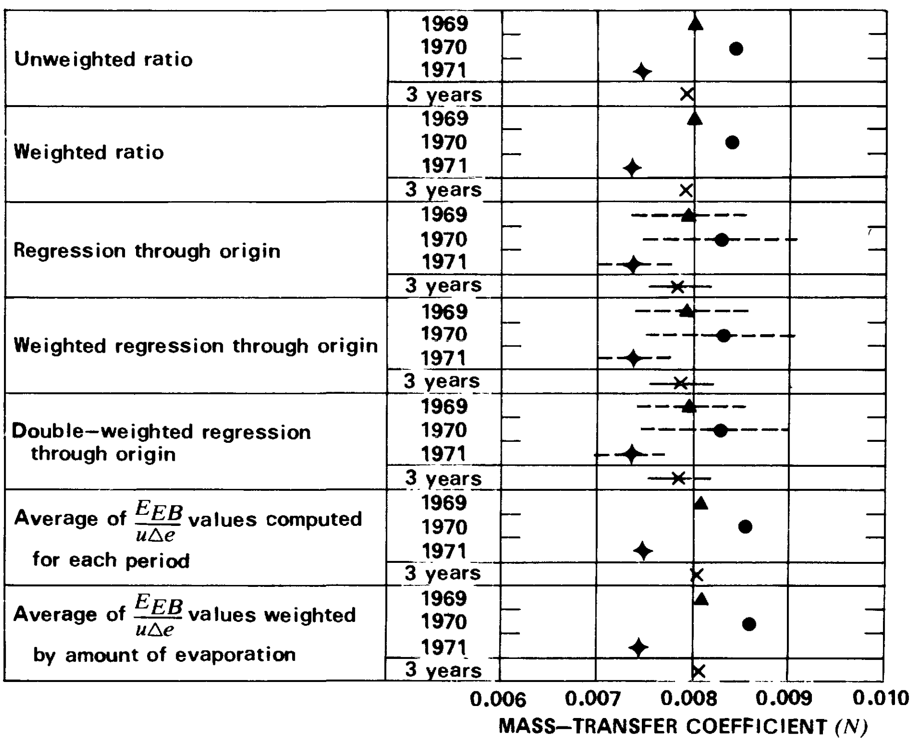

Figure 21.—Mass-transfer coefficients for Dillon Reservoir as determined by different means of calculation from the energy-budget data. Lines through some symbols represent 95-percent confidence limits.

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*

No.	Period: Length (days)	Period: Dates 1969	$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method: Centimeters per day	Reservoir evaporation computed by mass-transfer method: Centimeters per period	Reservoir evaporation computed by mass-transfer method: Acre-feet per period	Pan evaporation: Centimeters per period	Ratio of reservoir to pan evaporation
1	14	May 22- June 5	6.9	5.9	0.32	4.54	460.2	8.48	0.54
2	14	June 5- June 19	5.9	6.0	.28	3.94	425.9	5.36	.74
3	14	June 19- July 3	7.9	7.0	.44	6.16	667.2	8.03	.77
4	14	July 3- July 17	5.8	8.2	.38	5.30	571.7	8.89	.60
5	14	July 17- July 31	5.7	9.2	.42	5.84	626.4	7.58	.77
6	14	July 31- Aug. 14	6.2	11.5	.57	7.95	838.9	10.80	.74
7	14	Aug. 14- Aug. 28	6.1	11.2	.54	7.61	782.1	7.52	1.01
8	14	Aug. 28-Sept. 11	6.0	10.5	.50	7.02	705.8	6.30	1.11
9	14	Sept. 11-Sept. 25	5.7	10.1	.46	6.42	647.2	4.55	1.41
10	14	Sept. 25- Oct. 9	6.4	9.9	.50	7.06	705.4	3.28	2.15
11	15	Oct. 9- Oct. 24	7.5	6.6	.39	5.91	590.6	1.40	4.22
Record season	155	May 22- Oct. 24			0.44	67.75			
Pan season	155	May 22- Oct. 24			0.44	67.75		72.19	0.94

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
12	14	May 28- June 11	6.52	4.6	0.24	3.34	331.2	6.25	0.53
13	14	June 11- June 25	7.09	6.0	.34	4.74	472.5	9.83	.48
14	14	June 25- July 9	6.72	8.2	.44	6.14	650.7	10.82	.57
15	14	July 9- July 23	6.15	8.7	.43	5.96	643.6	8.36	.71
16	13	July 23- Aug. 5	5.96	9.7	.46	5.98	643.0	8.59	.70
17	15	Aug. 5- Aug. 20	5.91	9.6	.45	6.77	724.1	8.38	.81
18	14	Aug. 20-Sept. 3	5.66	9.0	.41	5.68	597.7	6.43	.88
19	14	Sept. 3-Sept. 17	8.06	8.6	.55	7.72	802.6	7.16	1.08
20	14	Sept. 17- Oct. 1	6.23	9.0	.45	6.25	643.3	4.95	.97
21	14	Oct. 1- Oct. 15	7.22	7.6	.44	6.11	627.3	----	----
Record season	140	May 28- Oct. 15			0.42	58.69			
Pan season	126	May 28- Oct. 1			0.42	52.58		70.77	0.74

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
22	7	June 3- June 10	7.75	4.4	0.27	1.90	195.1	6.25	0.30
23	14	June 10- June 24	6.75	4.7	.25	3.54	365.9	6.88	.51
24	14	June 24- July 8	7.38	7.9	.46	6.50	712.4	11.13	.52
25	14	July 8- July 22	6.72	8.4	.45	6.29	681.1	10.72	.59
26	14	July 22- Aug. 5	7.45	8.4	.50	6.97	750.5	8.43	.83
27	14	Aug. 5- Aug. 19	6.73	8.1	.43	6.07	653.9	9.27	.65
28	14	Aug. 19-Sept. 2	6.08	7.4	.36	5.01	507.3	7.04	.71
29	14	Sept. 2-Sept. 16	7.15	9.7	.55	7.73	762.7	8.15	.95
30	14	Sept. 16-Sept. 30	8.37	9.5	.63	8.86	872.7	5.79	1.53
31	14	Sept. 30- Oct. 14	7.54	6.8	.41	5.71	563.3	3.25	1.76
Record season	135	June 3- Oct. 14		--	0.43	58.58		--	--
Pan season	135	June 3- Oct. 14			0.43	58.58		76.91	0.76

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

	Period		$u_{2.0}$	e_o-e_a	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972	(miles per hour)	(millibars)	Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
32	6.0	June 9- June 15	6.43	5.6	0.285	1.70	187.9	3.61	.47
33	7.0	June 15- June 22	7.79	5.7	.351	2.47	271.0	2.77	.89
34	6.9	June 22- June 29	6.47	7.2	.371	2.58	281.0	4.70	.55
35	7.0	June 29- July 6	7.45	8.3	.492	3.46	375.4	5.94	.58
36	7.0	July 6- July 13	5.95	7.6	.360	2.51	268.5	4.32	.58
37	6.9	July 13- July 20	7.01	9.5	.533	3.70	386.8	6.15	.60
38	14.0	July 20- Aug. 3	6.8	9.5	.512	7.18	723.5	9.32	.77
39	7.0	Aug. 3- Aug. 10	6.90	9.8	.539	3.76	366.8	4.11	.91
40	7.0	Aug. 10- Aug. 17	6.10	9.4	.455	3.19	305.7	4.85	.66
41	7.0	Aug. 17- Aug. 24	6.31	8.3	.418	2.94	277.7	3.10	.95

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
42	6.9	Aug. 24- Aug. 31	6.24	7.8	0.387	2.69	252.6	2.77	0.97
43	7.0	Aug. 31-Sept. 7	6.70	7.9	.419	2.95	276.7	2.26	1.31
44	7.1	Sept. 7-Sept. 14	5.37	7.6	.324	2.29	214.5	2.16	1.06
45	6.9	Sept. 14-Sept. 21	7.32	9.2	.536	3.70	345.6	3.40	1.09
46	7.0	Sept. 21-Sept. 28	8.19	8.8	.575	4.02	376.6	2.97	1.35
47	7.0	Sept. 28- Oct. 5	7.15	7.7	.436	3.07	287.2	3.07	1.00
48	7.1	Oct. 5- Oct. 12	5.89	6.3	.293	2.08	195.0	1.70	1.22
49	6.9	Oct. 12- Oct. 19	5.89	4.9	.229	1.58	148.3	1.30	1.22
50	8.0	Oct. 19- Oct. 27	7.27	6.7	.388	3.10	290.0	1.88	1.65
Record season	139.7	June 9- Oct. 27			0.42	58.97			
Pan season	139.7	June 9- Oct. 27			0.42	58.97		71.68	0.82

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
51	7.1	June 14- June 21	8.69	4.6	0.318	2.25	244.6	5.13	0.44
52	6.9	June 21- June 28	6.87	5.8	.317	2.20	241.60	6.53	.34
53	7.0	June 28- July 5	6.89	8.9	.489	3.42	375.9	7.98	.43
54	7.0	July 5- July 12	6.88	8.7	.474	3.34	364.0	6.40	.52
55	7.0	July 12- July 19	5.75	4.8	.219	1.52	166.3	3.05	.50
56	7.1	July 19- July 26	6.90	6.5	.357	2.52	274.4	4.01	.63
57	6.9	July 26- Aug. 2	6.18	7.2	.352	2.48	263.5	4.62	.54
58	7.1	Aug. 2- Aug. 9	6.14	6.5	.318	2.42	242.5	3.96	.61
59	6.9	Aug. 9- Aug. 16	6.97	7.6	.419	2.91	313.8	5.69	.48
60	7.0	Aug. 16- Aug. 23	6.26	6.0	.299	2.09	224.9	4.50	.46
61	7.0	Aug. 23- Aug. 30	6.58	8.7	.453	3.19	343.5	4.50	.71

Table 7.--*Summary of mass-transfer terms and pan evaporation for Dillon Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
62	7.0	Aug. 30-Sept. 6	7.28	7.0	0.453	3.18	341.8	3.00	1.06
63	7.0	Sept. 6-Sept. 13	6.49	8.0	.415	2.88	309.9	4.34	.66
64	7.0	Sept. 13-Sept. 20	7.42	9.3	.548	3.83	412.0	3.91	.98
65	7.0	Sept. 20-Sept. 27	8.18	8.9	.582	4.07	437.5	3.18	1.28
66	7.0	Sept. 27- Oct. 4	7.16	7.1	.402	2.81	301.9	2.57	1.09
67	7.0	Oct. 4- Oct. 11	6.71	7.8	.418	2.93	311.3	2.11	1.39
68	7.0	Oct. 11- Oct. 18	6.77	6.9	.373	2.61	274.8	2.24	1.17
69	7.1	Oct. 18- Oct. 25	6.93	7.3	.401	2.83	295.6	2.90	.98
70	7.1	Oct. 25- Nov. 1	4.76	7.2	.274	1.95	201.7	2.03	.96
71	6.9	Nov. 1- Nov. 8	8.01	6.0	.384	2.66	273.9	.86	3.09
72	10.0	Nov. 8- Nov. 18	9.13	6.1	.440	4.41	448.7	2.31	1.91
Record season	157.1	June 14- Nov. 18			0.398	62.51			
Pan season	157.1	June 14- Nov. 18			0.398	62.51		85.82	0.73

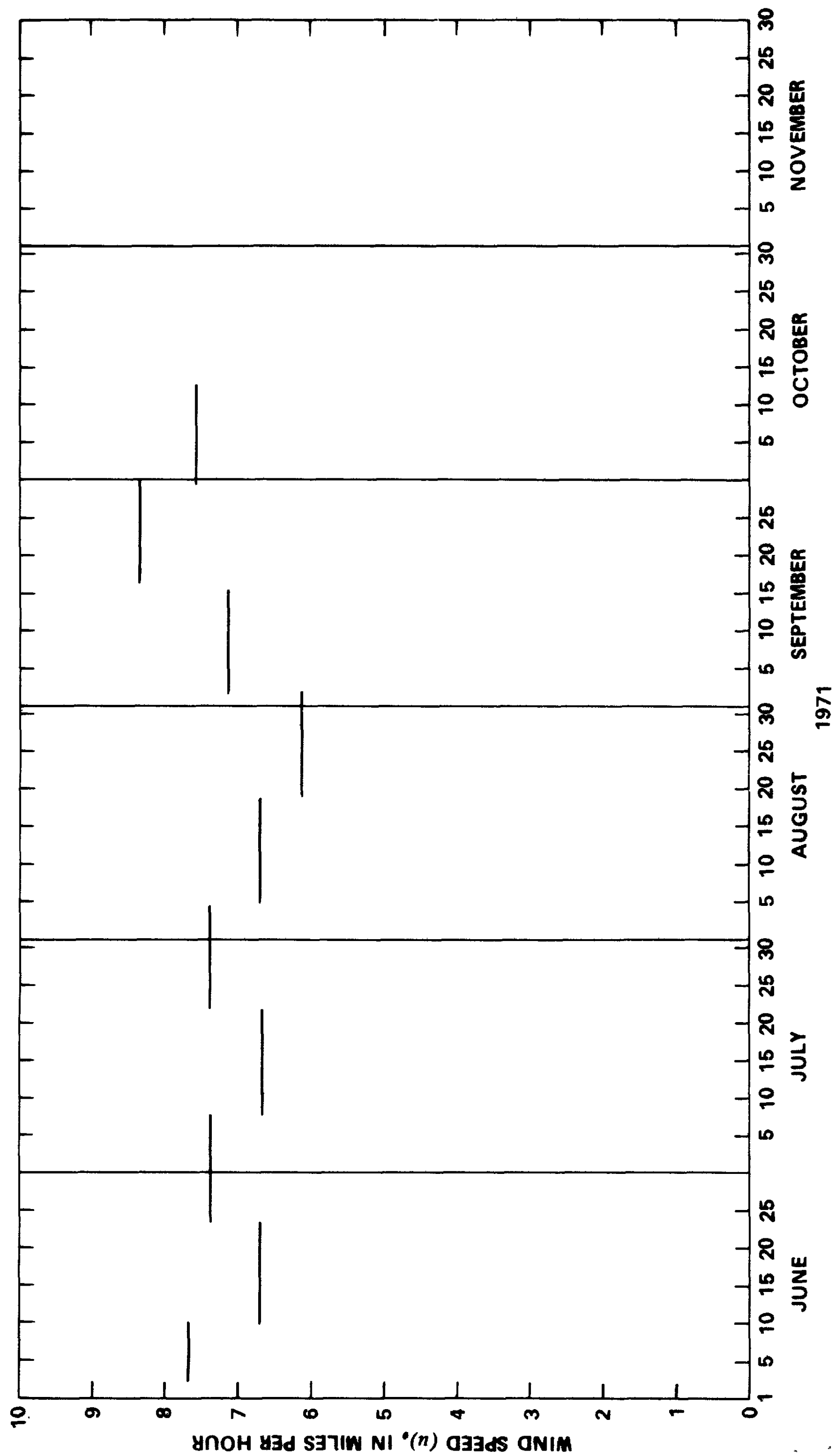

Figure 22.--Time graph of wind speeds, u, at Dillon Reservoir.

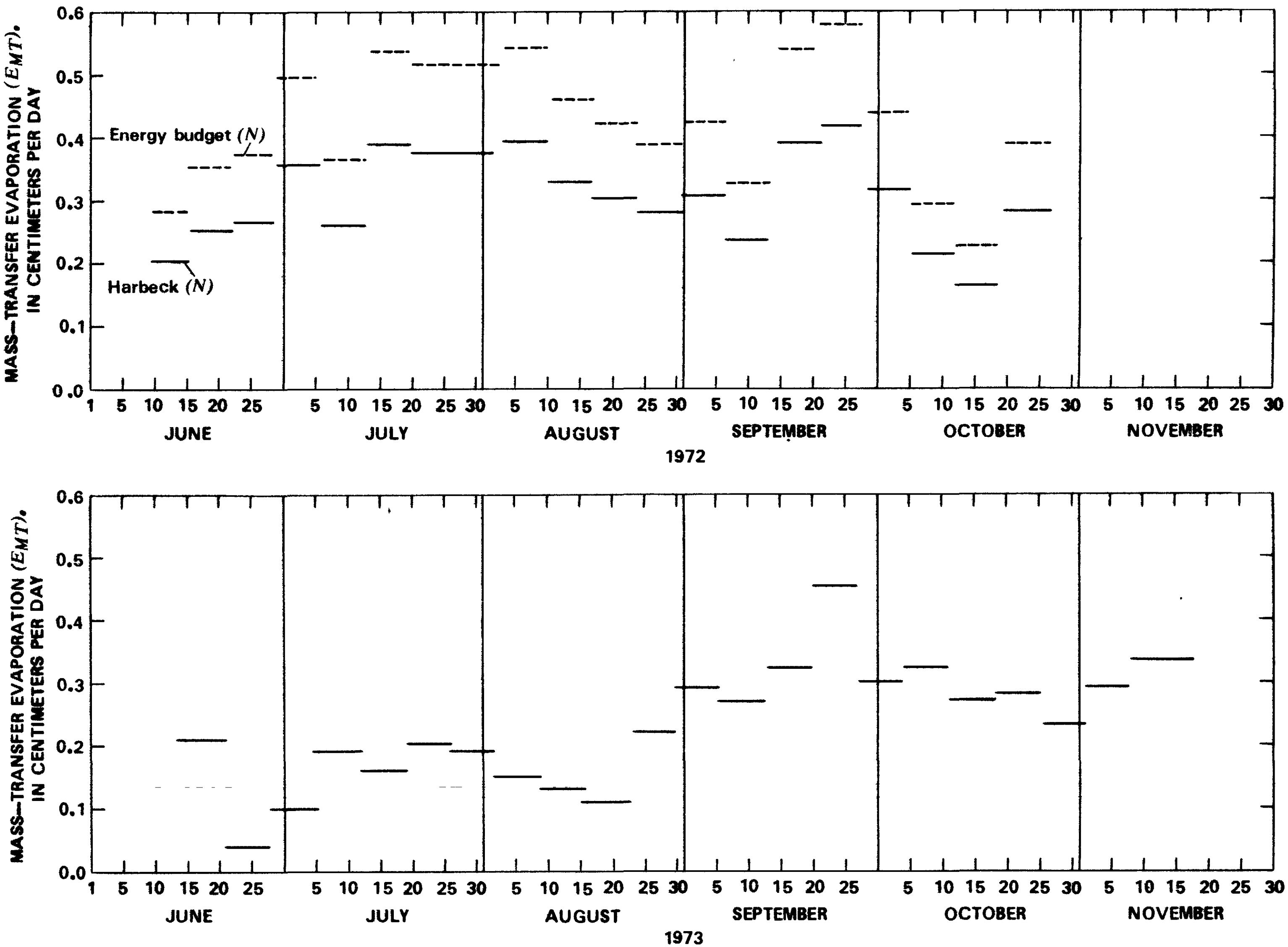

Figure 23.—Rates of mass–transfer evaporation, E_{MT}, from Dillon Reservoir for the 1972–73 record seasons.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Dillon Reservoir is listed in table 7 with the mass-transfer evaporation.

This evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratio also is listed and, as can be seen, the ratios vary moderately from season to season, and some are significantly different from the common 0.7 coefficient. The ratios for Dillon Reservoir are varied and have been calculated using mass-transfer evaporation as computed using N values derived from energy-budget data.

Corrections to pan evaporation for advected energy, based on equation 11, are listed in table 8. These corrections have very little meaning for Dillon Reservoir because of the high flow-through and rapid changes in storage. Discrepancies resulted from averaging of data between thermal surveys. These corrections are not applicable to reservoirs with short detention times or those experiencing rapid changes in volume.

Table 8.--*Advection and storage corrections for pan-based evaporation data for Dillon Reservoir*

Period			Q_v	Q_w	Q_x		Evaporation effect, ΔE	
No.	Length (days)	Dates 1969	Cal cm^{-2} d^{-1}			α	Centimeters per day	Centimeters per period
1	14	May 22- June 5	94	3	452	0.42	-0.26	-3.59
2	14	June 5- June 19	-27	3	57	.44	- .06	- .91
3	14	June 19- July 3	-78	5	164	.47	- .20	-2.75
4	14	July 3- July 17	-59	6	151	.48	- .18	-2.46
5	14	July 17- July 31	-12	7	93	.50	- .10	-1.35
6	14	July 31- Aug. 14	5	10	92	.51	- .08	-1.18
7	14	Aug. 14- Aug. 28	6	9	- 23	.51	.02	.24
8	14	Aug. 28-Sept. 11	10	8	- 48	.50	.04	.60
9	14	Sept. 11-Sept. 25	7	5	- 87	.49	.07	1.04
10	14	Sept. 25- Oct. 9	1	7	-240	.48	.19	2.67
11	15	Oct. 9- Oct. 24	- 6	3	-251	.43	.18	2.64
Record season	155	May 22- Oct. 24						-5.05

Table 8.--*Advection and storage corrections for pan-based evaporation data for Dillon Reservoir*--Continued

Period			Q_v	Q_w	Q_x	α	Evaporation effect, ΔE	
No.	Length (days)	Dates 1970	Cal cm^{-2} d^{-1}				Centimeters per day	Centimeters per period
12	14	May 28- June 11	-11	2	313	0.40	-0.22	-3.07
13	14	June 11- June 25	76	5	383	.46	- .24	-3.39
14	14	June 25- July 9	85	7	304	.48	- .18	-2.58
15	14	July 9- July 23	-77	8	84	.50	- .14	-2.00
16	13	July 23- Aug. 5	-50	9	60	.51	- .10	-1.34
17	15	Aug. 5- Aug. 20	-32	8	29	.51	- .06	- .90
18	14	Aug. 20-Sept. 3	-12	7	-24	.49	.00	.06
19	14	Sept. 3-Sept. 17	- 3	7	-59	.51	.02	.28
20	14	Sept. 17- Oct. 1	-26	5	-122	.46	.07	.99
21	14	Oct. 1- Oct. 15	-24	4	-224	.45	.15	2.09
Record season	140	May 28- Oct. 15						-9.86

Period			Q_v	Q_w	Q_x	α	Evaporation effect, ΔE	
No.	Length (days)	Dates 1971	Cal cm^{-2} d^{-1}				Centimeters per day	Centimeters per period
22	7	June 3- June 10	30	2	250	0.42	-0.16	-1.10
23	14	June 10- June 24	52	2	367	.45	- .24	-3.37
24	14	June 24- July 8	-171	6	16	.48	- .16	-2.20
25	14	July 8- July 22	-80	6	117	.49	- .17	-2.36
26	14	July 22- Aug. 5	-43	7	7	.50	- .05	- .60
27	14	Aug. 5- Aug. 19	-20	5	118	.50	- .12	-1.70
28	14	Aug. 19-Sept. 2	-10	5	53	.50	- .06	- .81
29	14	Sept. 2-Sept. 16	5	8	-97	.50	.08	1.12
30	14	Sept. 16-Sept. 30	4	7	-252	.48	.20	2.83
31	14	Sept. 30- Oct. 14	1	3	-66	.44	.05	.67
Record season	133	June 3- Oct. 14						-7.60

EVAPORATION FROM GROSS RESERVOIR

Gross Reservoir, located about 30 mi (48.3 km) northwest of Denver, is formed by a gravity-arch concrete dam on South Boulder Creek. The dam, which was completed in 1954, is 340 ft (103.6 m) high, with its spillway crest at an altitude of 7,282 ft (2,200.4 m) above sea level. When full, the reservoir holds 41,811 acre-ft (51.6 hm^3) of water, and has a surface area of 415 acres (1.68 km^2). Waters stored in Gross Reservoir are those diverted from west of the Continental Divide through the Moffat Tunnel and also those diverted from South Boulder Creek (fig. 1). Gross Reservoir has the greatest depth, 297 ft (97.4 m), and the greatest mean depth, 100.8 ft (30.7 m), of the reservoirs studied.

Measurements of evaporation at Gross Reservoir were started in 1972. Evaporation was measured by means of energy-budget, mass-transfer, and standard-pan methods during the 1972 and 1973 seasons.

Instruments for measuring wet-bulb and dry-bulb temperatures and radiation were located atop Gross Dam. A standard class-A pan was mounted on top of the dam. Temperature of the water surface and average wind speed were measured by equipment on a raft anchored near the center of the reservoir.

Energy-Budget Parameters

Data for solar radiation (Q_s) are from a pyranometer installed atop the dam. Short periods of missing pyranometer data were filled in by estimates based upon tabulated values of clear sky radiation and observed cloud cover. A time graph of solar-radiation (Q_s) values recorded at Gross Reservoir during 1972 is shown on figure 24. The values are based upon daily integrator readings from the recorder. Records of wet-bulb and dry-bulb temperatures were computed largely from the integrator records of the recorder connected to the psychrometer described earlier. Except for minor difficulties caused by broken thermocouple leads, the records were quite complete. It was difficult to evaluate the effect of freezing upon the wet-bulb temperature record. Consequently, most vapor-pressure records for periods of psychrometer reservoir freezing were estimated from hygrothermograph records at the reservoir. As indicated by the vapor-pressure records, the values of air vapor pressure (e_a) were recorded daily (fig. 25) and were then averaged over the number of days between thermal surveys for computation of evaporation. Errors could be expected to result from this type of computation because the relationship between temperature and vapor pressure is not linear. On the other hand, the errors are small and the cost of additional accuracy afforded by more frequent thermal surveys could not be justified.

Values of saturation vapor pressure at the temperature of the water surface (e_o) were selected from tables of the saturation vapor pressure of water, as functions of daily mean temperature (T_o) (fig. 26) computed from records of the thermograph or thermistor on the raft in the center of the lake. Record of e_o for 1972 is shown on figure 25.

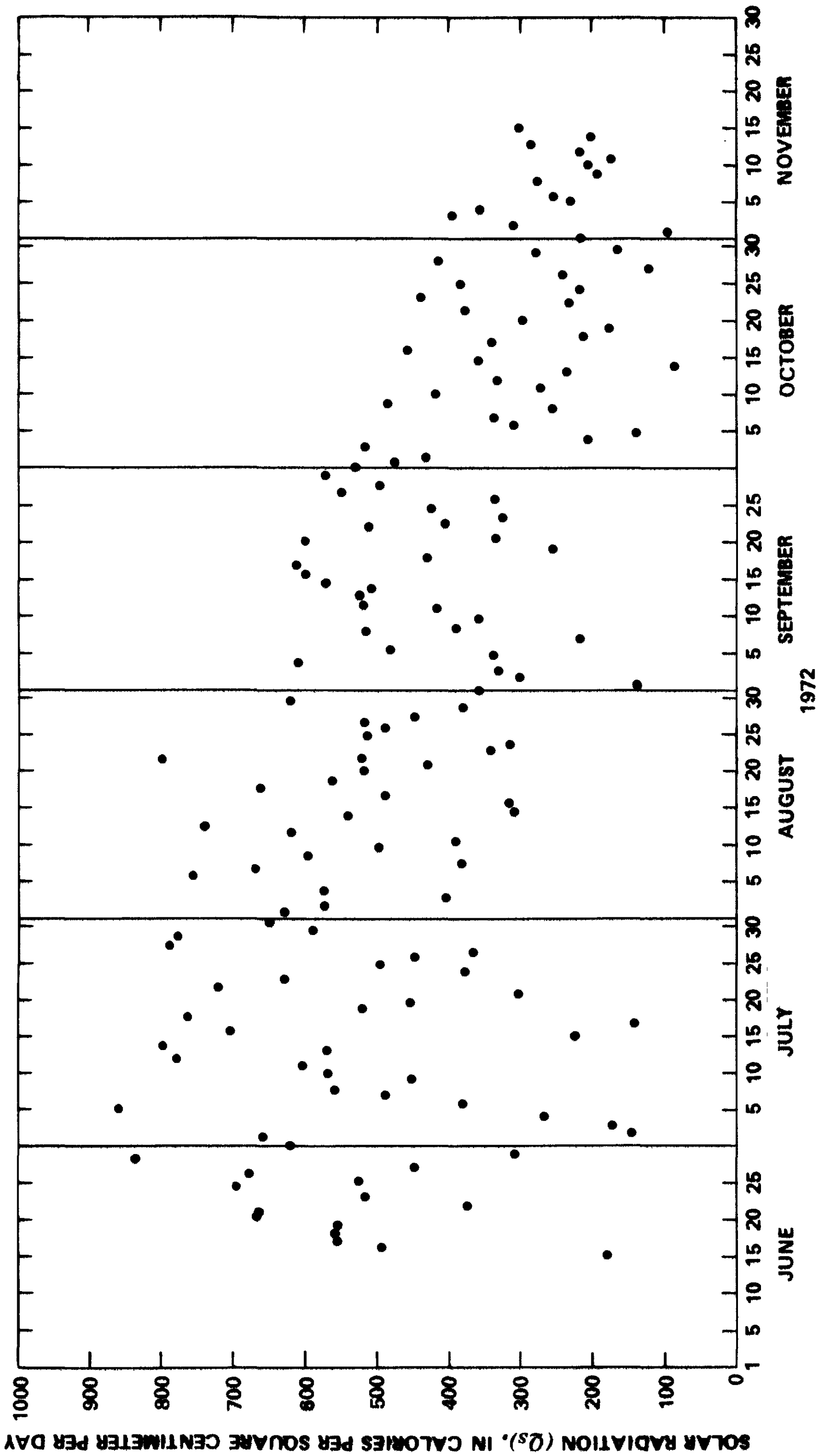

Figure 24.—Time graph of solar radiation, Q_S, measured at Gross Reservoir.

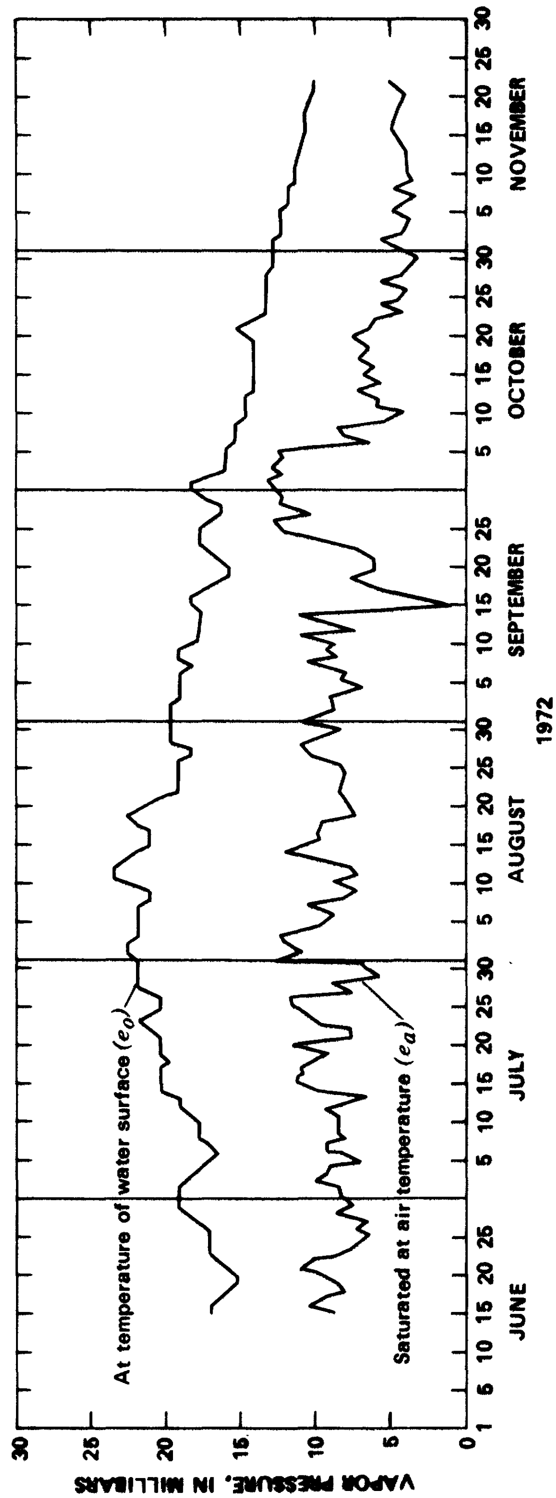

Figure 25.—Time graph of vapor pressures, e_o and e_a at Gross Reservoir.

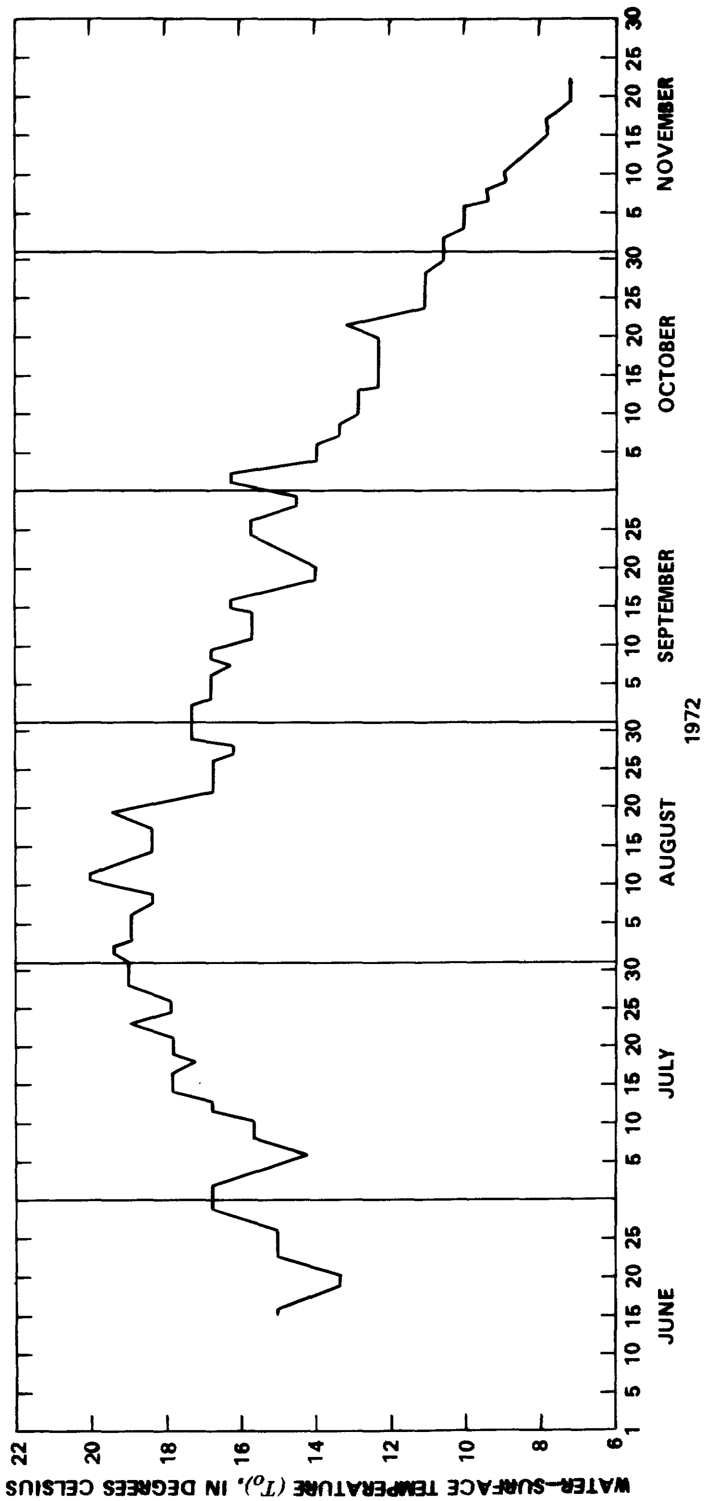

Figure 26.—Time graph of water-surface temperature, T_o, of Gross Reservoir.

Temperature-survey data were used to compute the mean temperature in each reservoir layer. The energy in each layer, measured above a base of 0°C, was computed as the product of temperature and the volume of the layer. Finally, average storage, in calories per square centimeter, was computed as the sum of the individual layers divided by the surface area of the reservoir. Changes in stored energy between any two surveys, divided by the length of the period, yielded the term Q_x, in calories per square centimeter per day (see equation 10).

Volumes used in the computation of energy storage were computed from a capacity table supplied by the Denver Board of Water Commissioners. Computation of evaporation would not be affected by errors in the capacity table during those periods when there is little or no change in heat storage. The greatest error would be expected during periods of rapid heating during the spring and early summer.

It is obvious that reliable values of Q_x can be computed only between two accurate measurements of energy storage. Consequently, solutions of the energy-budget formula are limited to those periods between major temperature surveys.

Volume and temperature records for rainfall, inflow, and outflow were used to compute advected energy (Q_v). Advected energy is a relatively small term in the energy budgets of reservoirs having large ratios of volume/flow-through, but it is of considerable proportion in Gross Reservoir, which is drawn down by a large amount each year.

In reporting values of Q_v, it sometimes is convenient to combine the Q_v data with data on changes in energy storage (Q_x), and to report the difference (Q_v-Q_x). The combination Q_v-Q_x represents the combined last two terms of the numerator in equation 6. Values of Q_v-Q_x for Gross Reservoir for the 1972 record season are shown in figure 27.

Energy-Budget Records

Records of evaporation from Gross Reservoir, as computed from the energy budget for the 1972 and 1973 seasons, are summarized in table 9. The evaporation rates also are shown graphically in the evaporation hydrographs on figure 28. Rates of evaporation measured during the 1972 season varied within the rather narrow range of 0.292 to 0.562 cm/d. However, rates measured during the 1973 season varied considerably more, with three periods in June and July having rates less than 0.11 cm/d, and one period having a very high rate of 1.033 cm/d. Earlier studies by Ficke (1972) showed that the energy-budget method is least reliable during the spring periods, and it therefore is probable that the very low evaporation rates during June and July of 1973 could have been in error.

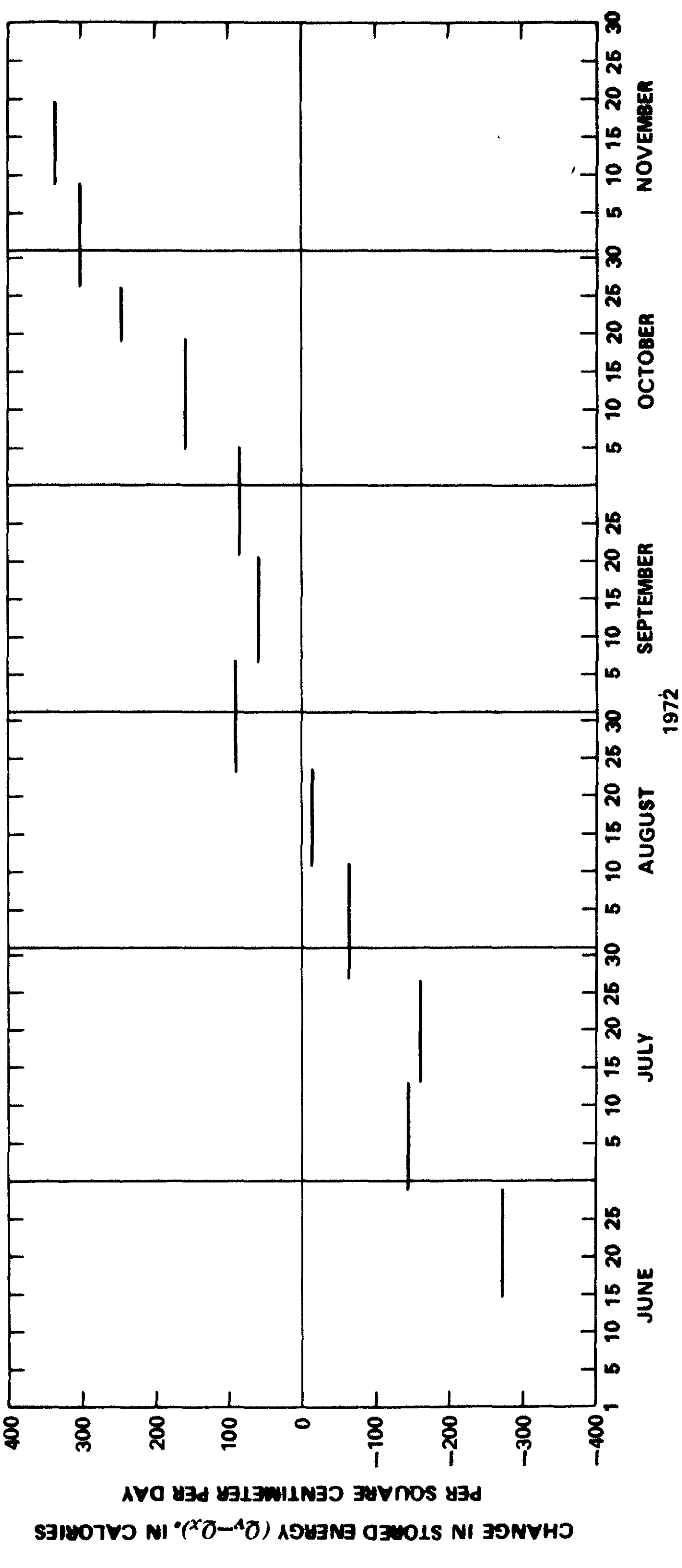

Figure 27.—Time graph of advected energy minus changes in stored energy, Q_v-Q_x, for Gross Reservoir.

Table 9.--*Summary of energy-budget terms and evaporation computation for Gross Reservoir*

Period			Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation	
No.	Length (days)	Dates 1972	Cal cm^{-2} d^{-1}										Centimeters per day	Centimeters per period
1	13.96	June 15- June 29	582	37	676	778	158	430	175	- 9	4	-0.051	0.298	4.16
2	13.99	June 29- July 13	511	33	638	791	80	223	178	- 1	5	- .005	.303	4.23
3	13.98	July 13- July 27	526	34	664	813	-56	104	175	3	5	.016	.298	4.16
4	14.99	July 27- Aug. 11	602	38	673	824	-66	-2	330	8	11	.024	.562	8.42
5	13.78	Aug. 11- Aug. 24	472	33	646	819	-185	-172	232	13	7	.057	.394	5.44
6	13.25	Aug. 24-Sept. 7	431	31	632	801	-26	-108	263	43	7	.165	.448	5.93
7	13.97	Sept. 7-Sept. 21	479	35	590	787	-127	-182	275	19	7	.070	.468	6.54
8	13.97	Sept. 21- Oct. 5	436	33	552	782	-254	-335	179	71	5	.395	.304	4.24
9	13.97	Oct. 5- Oct. 19	306	26	579	757	-208	-367	209	48	5	.230	.355	4.96
10	7.06	Oct. 19- Oct. 26	322	27	598	749	-105	-349	286	96	6	.338	.484	3.41
11	12.78	Oct. 26- Nov. 7	256	23	462	732	-50	-350	173	87	3	.506	.292	3.73
12	16.00	Nov. 7- Nov. 22	234	22	445	709	-89	-421	163	114	2	.698	.275	4.40
Record season	161.70	June 15- Nov. 22	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	0.369	59.62

Table 9.--*Summary of energy-budget terms and evaporation computation for Gross Reservoir*--Continued

No.	Length (days)	Dates 1973	Q_s	Q_r	Q_a-Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w	Bowen ratio R	Evaporation: Centimeters per day	Evaporation: Centimeters per period
			Cal cm^{-2} d^{-1}											
13	14.19	May 31- June 14	689	41	749	747	-227	260	195	-37	4	-0.190	0.331	4.69
14	14.05	June 14- June 28	712	43	670	772	-244	284	39	- 1	1	- .025	.066	.93
15	13.95	June 28- July 12	615	38	715	808	-116	332	39	- 4	1	- .109	.067	.93
16	14.05	July 12- July 26	440	30	635	807	- 51	113	62	10	2	.168	.105	1.48
17	14.00	July 26- Aug. 9	537	35	697	804	18	127	272	6	8	.023	.463	6.48
18	13.95	Aug. 9- Aug. 23	604	40	837	806	-149	-111	607	-67	18	- .110	1.033	14.41
19	13.97	Aug. 23-Sept. 6	410	28	768	801	-251	-323	396	13	11	.033	.673	9.40
20	14.03	Sept. 6-Sept. 20	416	31	588	784	-209	-199	153	22	4	.142	.260	3.65
21	14.01	Sept. 20- Oct. 4	363	27	549	771	41	- 97	190	56	5	.295	.322	4.50
22	13.99	Oct. 4- Oct. 18	352	29	550	756	- 1	-135	210	36	4	.173	.356	4.98
23	19.97	Oct. 18- Nov. 7	302	27	516	742	- 9	-234	212	58	4	.275	.358	7.15
24	6.03	Nov. 7- Nov. 13	278	25	438	725	- 40	-207	140	-11	2	- .076	.237	1.43
25	13.93	Nov. 13- Nov. 27	243	23	322	716	-215	-571	112	68	2	.606	.190	2.64
Record season	180.12	May 31- Nov. 27	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	0.348	62.67

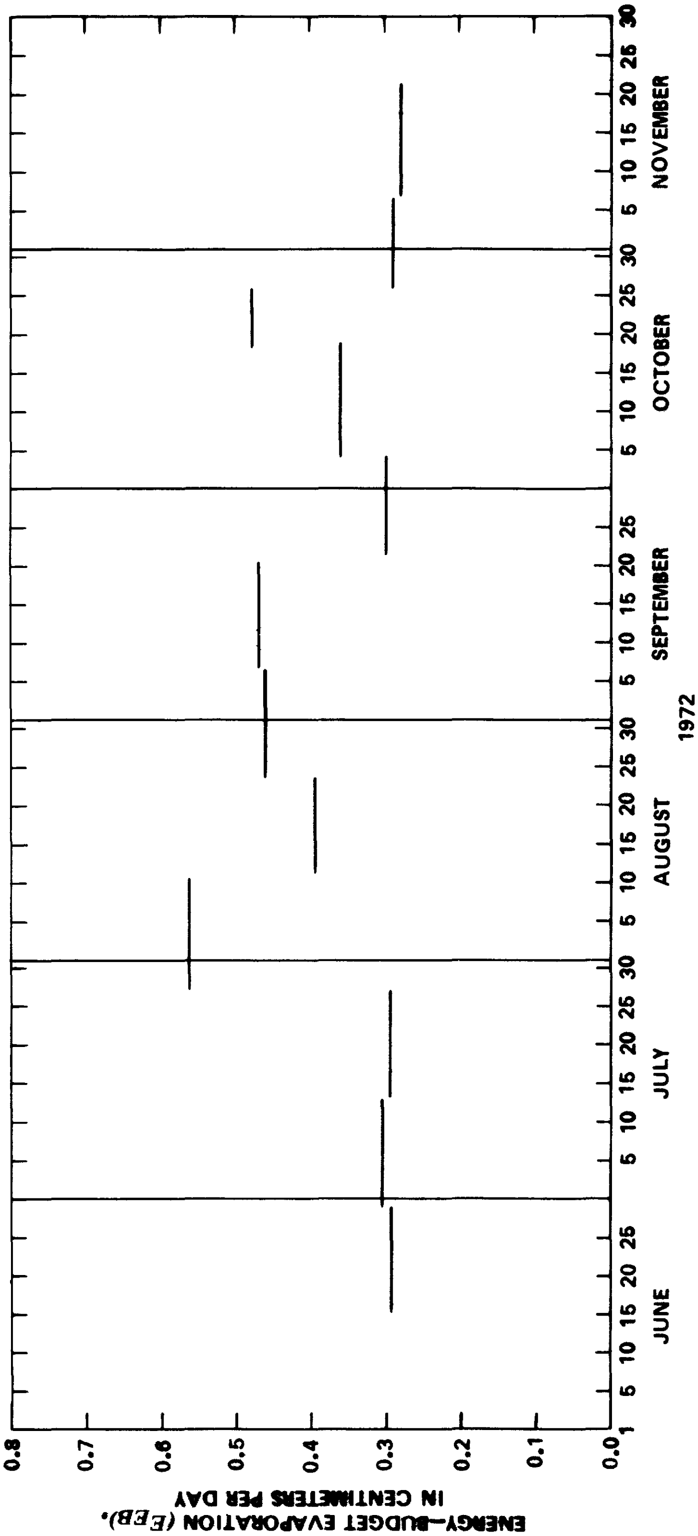

Figure 28.--Rates of energy-budget evaporation, E_{EB}, from Gross Reservoir for the 1972-73 record seasons.

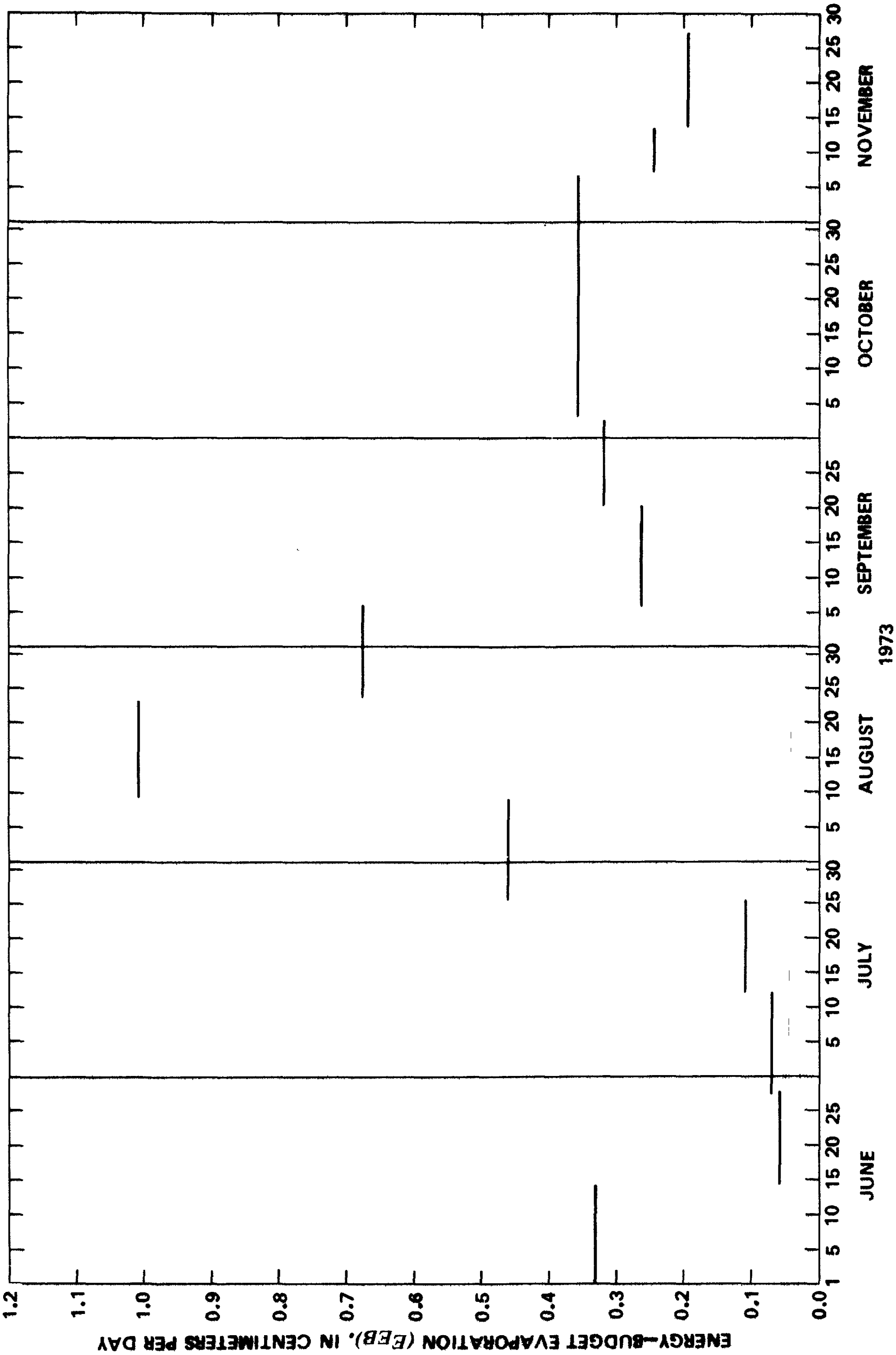

Figure 28.—Rates of energy-budget evaporation, E_{EB}, from Gross Reservoir for the 1972–73 record seasons—Continued.

Mass-Transfer Records

Calibration of the coefficient.--The mass-transfer coefficient, N, for Gross Reservoir was determined using the 1972 and 1973 records of evaporation as computed by the energy-budget technique. A plot of energy-budget values against the mass-transfer products, $u_2(e_o - e_a)$, is given on figure 29. The slope of the relation line defined by the plot on figure 29 is equal to the value of N for Gross Reservoir.

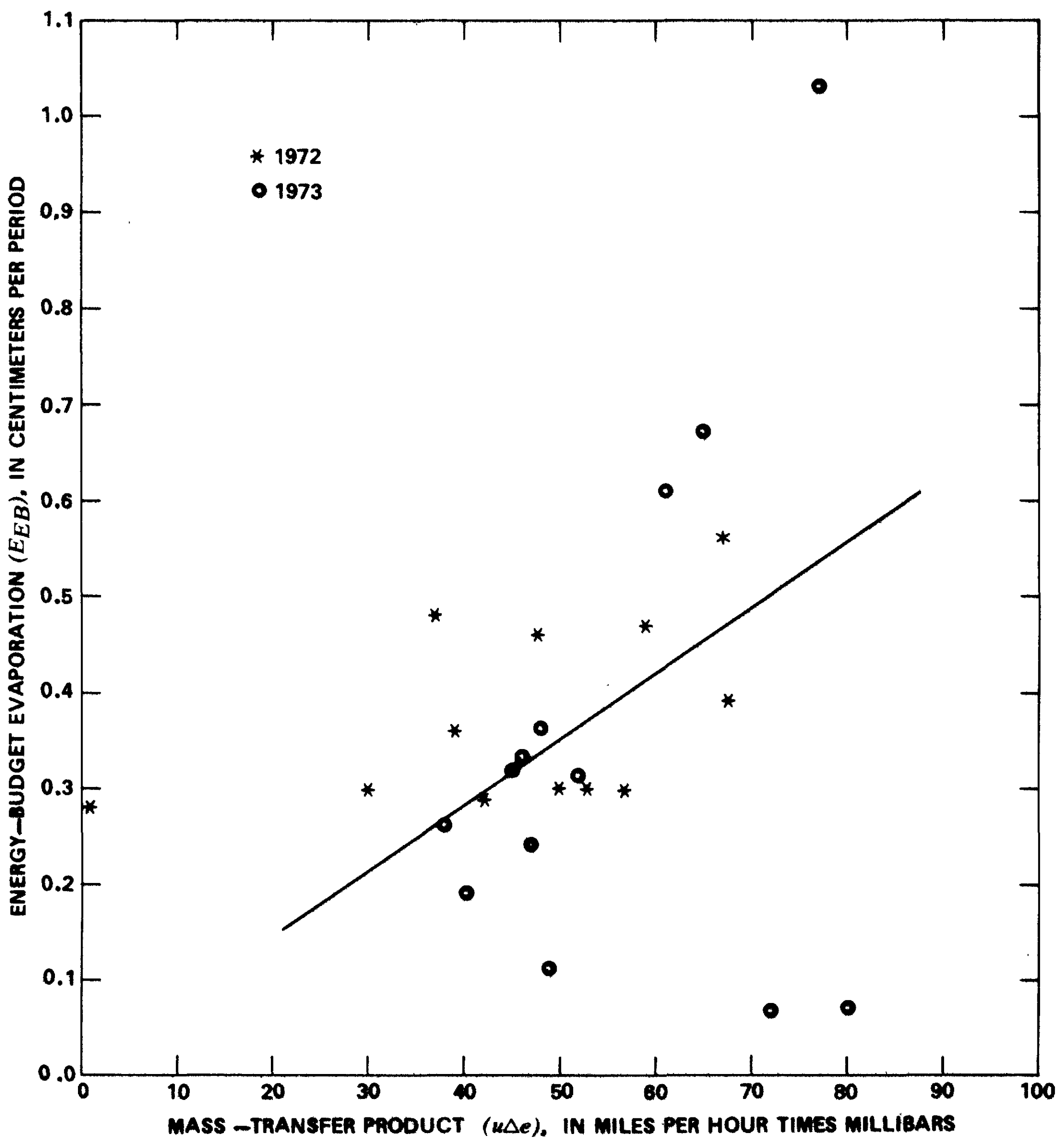

Figure 29.—Calibration plot of the mass-transfer product against evaporation as measured by the energy-budget method at Gross Reservoir, 1972–73.

Several techniques were used to fit a relation line to the data on figure 29. These were the same techniques that were briefly described in the section giving records for Elevenmile Canyon Reservoir (p. 26-36). Values of N, as computed by the different techniques, are given on figure 30. Dashed lines through some of the symbols on figure 30 represent 95-percent confidence limits for the regression coefficients.

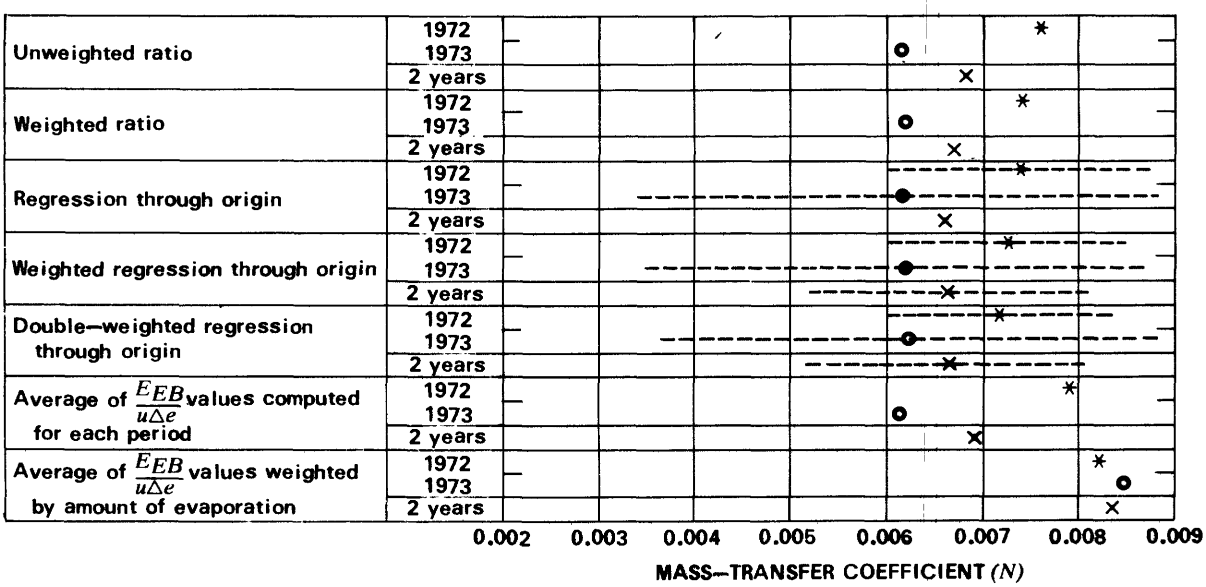

Figure 30.—Mass-transfer coefficients for Gross Reservoir as determined by different means of calculation from the energy-budget data. Lines through some symbols represent 95-percent confidence limits.

A value of N of 0.0069 was selected for use in mass-transfer computations for Gross Reservoir. As shown by the plot on figure 29, and the summary on figure 30 data for 1972 define a higher N value than do 1973 data. Part of the difference is attributed to the suspected errors in the energy-budget data for several periods in 1973.

The values of N for Gross Reservoir, as determined by Harbeck's equation (equation 8 of this report), was 0.00636. Harbeck's N fell within the confidence intervals for N values defined by 1973 data and within the intervals defined by 2 years of data. The N value of 0.0069 determined for Gross Reservoir is within the range of expected variations of values determined by Harbeck's relationship.

Data.--Saturation vapor pressure at the water surface varies directly with temperature, so that the pattern on the top line of figure 25 very nearly resembles the pattern of the thermograph on figure 26. Vapor pressure of the air varies considerably from one day to the next and obviously results in considerable day-to-day differences in evaporation. As figure 31 shows, wind speed, as averaged over 2-week intervals (time between thermal surveys), varies generally in the range of 4.5 to 6 mi/h (2.0 to 2.7 m/s) for the 1972 season. Evaporation records for Gross Reservoir as determined by the mass-transfer method, using N = 0.0069, are given in table 10. Computation periods for mass-transfer data are the same as those used for the energy budget (table 9). Evaporation rates, as computed by the mass-transfer method, are plotted on figure 32.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Gross Reservoir is listed in table 10 with the mass-transfer evaporation.

This evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratio is also listed and, as can be seen, the ratios differ moderately from season to season, and some are significantly different from the common 0.7 coefficient. The ratios for Gross Reservoir are varied. They have been computed using data on mass-transfer evaporation.

Corrections for advected energy to pan evaporation, based on equation 11, are listed in table 11. These corrections have very little meaning for Gross Reservoir because of the high flow-through and rapid changes in storage. Discrepancies resulted from the averaging of data between thermal surveys. These corrections are not applicable to reservoirs with short detention times or those experiencing rapid changes in volume.

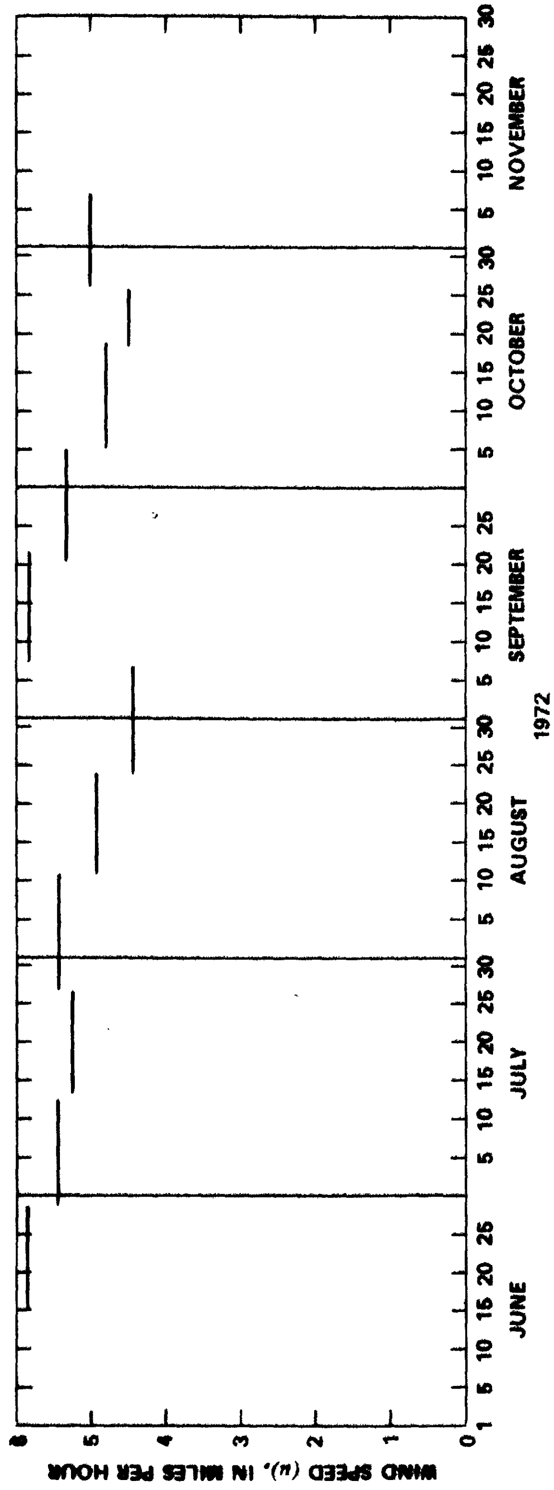

Figure 31.—Time graph of wind speeds, u, at Gross Reservoir.

Table 10.--*Summary of mass-transfer terms and pan evaporation for Gross Reservoir*

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	13.96	June 15- June 29	5.78	8.6	0.343	4.79	63.65	----	----
2	13.99	June 29- July 13	5.41	9.7	.362	5.06	68.39	8.99	0.56
3	13.98	July 13- July 27	5.29	10.8	.394	5.51	72.76	9.96	.55
4	14.99	July 27- Aug. 11	5.37	12.5	.463	6.94	85.58	12.84	.54
5	13.78	Aug. 11- Aug. 24	5.40	12.5	.466	6.42	73.91	9.32	.69
6	13.25	Aug. 24-Sept. 7	4.87	9.9	.333	4.41	47.93	6.17	.71
7	13.97	Sept. 7-Sept. 21	5.83	10.1	.406	5.68	59.66	8.31	.68
8	13.97	Sept. 21- Oct. 5	5.26	5.8	.211	2.94	29.05	7.85	.37
9	13.97	Oct. 5- Oct. 19	4.78	8.1	.267	3.73	34.27	4.95	.75
10	7.06	Oct. 19- Oct. 26	4.48	8.3	.257	1.81	16.22	1.24	1.46
11	12.78	Oct. 26- Nov. 7	5.03	8.3	.288	3.68	32.80	----	----
Record season	145.70	June 15- Nov. 7			0.350	50.97			
Pan season	118.96	June 29- Oct. 26			0.357	42.50		69.93	0.61

Table 10.--*Summary of mass-transfer terms and pan evaporation for Gross Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
13	14.19	May 31- June 14	7.33	6.3	0.3176	4.52	61.39	11.33	0.40
14	14.05	June 14- June 28	8.46	9.4	.548	7.70	103.95	13.77	.56
15	13.95	June 28- July 12	6.54	11.0	.496	6.92	93.62	14.81	.47
16	14.05	July 12- July 26	5.10	9.5	.334	4.69	62.59	8.51	.55
17	14.00	July 26- Aug. 9	6.18	9.8	.418	5.85	76.77	10.49	.56
18	13.95	Aug. 9- Aug. 23	7.88	9.8	.533	7.43	92.24	12.52	.59
19	13.97	Aug. 23-Sept. 6	5.63	12.0	.466	6.51	73.87	10.34	.63
20	14.03	Sept. 6-Sept. 20	4.22	9.1	.265	3.71	38.46	8.26	.45
21	14.01	Sept. 20- Oct. 4	4.54	10.1	.316	4.43	46.14	6.58	.67
22	13.99	Oct. 4- Oct. 18	5.21	9.3	.334	4.67	49.88	6.12	.76
23	19.97	Oct. 18- Nov. 17	5.69	9.2	.361	7.21	78.53	----	----
24	6.03	Nov. 7- Nov. 13	6.52	7.6	.342	2.06	22.77	----	----
25	13.93	Nov. 13- Nov. 27	5.92	6.8	.278	3.86	39.99	----	----
Record season	180.12	May 31- Nov. 27			0.386	69.56			
Pan season	140.19	May 31- Oct. 18			0.403	56.43		102.73	0.55

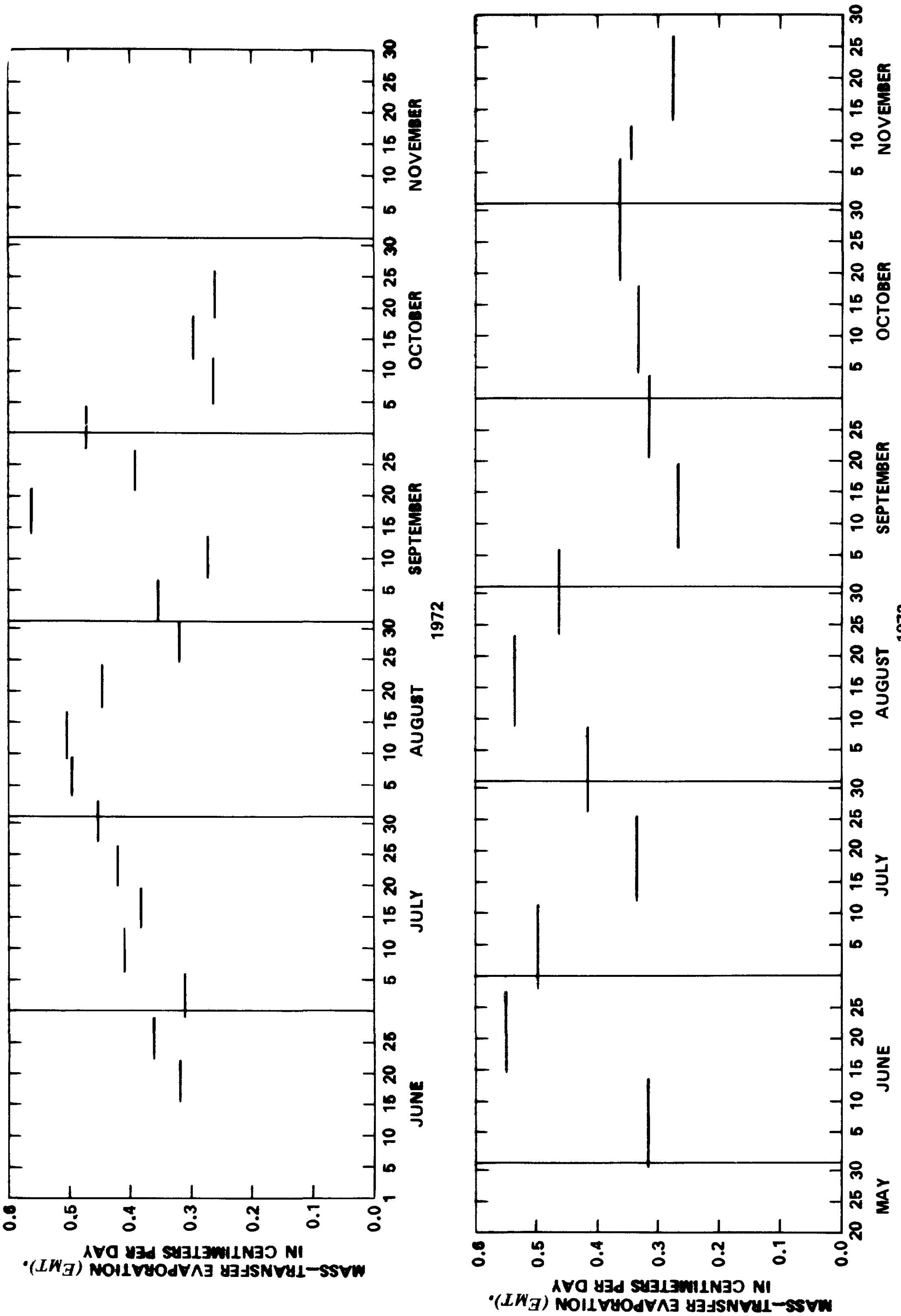

Figure 32.—Rates of mass-transfer evaporation, E_{MT}, from Gross Reservoir for the 1972–73 record seasons.

Table 11.--*Advection and storage corrections for pan-based evaporation data for Gross Reservoir*

Period			Q_v	Q_w	Q_x	α	Evaporation effect, ΔE	
No.	Length (days)	Dates 1972	Cal	cm^{-2}	d^{-1}		Centimeters per day	Centimeters per period
1	13.96	June 15- June 29	158	4	430	0.48	-0.225	-3.14
2	13.99	June 29- July 13	80	5	223	.47	- .118	-1.66
3	13.98	July 13- July 27	- 56	5	104	.51	- .143	-2.01
4	14.99	July 27- Aug. 11	- 66	11	- 2	.52	- .066	-1.00
5	13.78	Aug. 11- Aug. 24	-185	7	-172	.50	- .017	- .22
6	13.25	Aug. 24-Sept. 7	- 26	7	-108	.46	.059	.81
7	13.97	Sept. 7-Sept. 21	-127	7	-182	.50	.041	.57
8	13.97	Sept. 21- Oct. 5	-254	5	-335	.47	.061	.85
9	13.99	Oct. 5- Oct. 19	-208	5	-367	.43	.112	1.57
10	7.06	Oct. 19- Oct. 26	-105	6	-349	.41	.165	1.17
Record season	132.99	June 15- Oct. 26						-3.06

Period			Q_v	Q_w	Q_x	α	Evaporation effect, ΔE	
No.	Length (days)	Dates 1973	Cal	cm^{-2}	d^{-1}		Centimeters per day	Centimeters per period
13	14.19	May 31- June 14	-227	4	260	0.40	-0.332	-4.72
14	14.05	June 14- June 28	-244	1	284	.50	- .449	-6.31
15	13.95	June 28- July 12	-116	1	332	.50	- .382	-5.33
16	14.05	July 12- July 26	- 51	2	113	.50	- .141	-1.98
17	14.00	July 26- Aug. 9	18	8	127	.51	- .102	-1.42
18	13.95	Aug. 9- Aug. 23	-149	18	-111	.53	- .050	- .70
19	13.97	Aug. 23-Sept. 6	-251	11	-323	.50	.052	.72
20	14.03	Sept. 6-Sept. 20	-209	4	-199	.42	- .010	- .14
21	14.01	Sept. 20- Oct. 4	41	5	- 97	.48	.108	1.52
22	13.99	Oct. 4- Oct. 18	- 1	4	-135	.44	.098	1.38
23	19.97	Oct. 18- Nov. 7	- 9	4	-234	.44	.164	3.29
24	6.03	Nov. 7- Nov. 13	- 40	2	-207	.42	.117	.71
25	13.93	Nov. 13- Nov. 27	-215	2	-571	.39	.233	3.25
Record season	180.12	May 31- Nov. 27						-9.73

EVAPORATION FROM ANTERO RESERVOIR

The earthfill dam impounding Antero Reservoir was completed by the Antero and Lost Park Reservoir Co. in 1909. In 1924 the reservoir was purchased by the Denver Board of Water Commissioners for use as part of the Denver water-supply system.

Although Antero Reservoir has the capacity to store in excess of 85,000 acre-ft (104.8 hm^3), the Denver Board of Water Commissioners presently operates that facility with only 15,878 acre-ft (19.6 hm^3) in storage. At this level, the mean depth is 8 ft (2.44 m), the altitude is 8,978 ft (2,736.5 m), and the surface area is 1,931 acres (7.81 km^2).

Evaporation from Antero Reservoir was measured by mass-transfer and pan techniques for 5 years, 1967-71. The mass-transfer calculations from existing and future data can be improved by N-value calibration from future energy-budget studies. The hygrothermograph for obtaining vapor-pressure data, e_a, and the class-A pan station were located near the caretaker's facilities on the south side of the reservoir. Wind speed and water temperature were recorded by instruments on a raft anchored near the center of the reservoir.

Mass-Transfer Records

Independent measurements of evaporation by the energy-budget method were not available for calibration of the mass-transfer coefficient for Antero Reservoir. Consequently, the value of the coefficient, N, for Antero Reservoir was computed to be 0.0059 using Harbeck's relationship (equation 8 of this report) and the nominal reservoir size of 1,931 acres (7.81 km^2).

Table 12 summarizes evaporation records for Antero Reservoir as computed by the mass-transfer method for 5 years, 1967-71. Computation periods shown generally have lengths of 7 days, corresponding to periods between readings of the dial on the totalizing anemometer. Evaporation hydrographs showing rates of evaporation from Antero Reservoir are shown on figure 33. Rates of evaporation measured during the record season are shown to vary greatly from week to week, ranging from less than 0.2 cm/d to more than 0.6 cm/d during the season.

Records of water temperature, vapor pressure, and wind speed measured during the 1971 record season are presented on figures 34, 35, and 36, to illustrate the ranges of these variables. As figure 34 shows, water temperature rarely exceeds 17°C during the season, reflecting the high elevation of the reservoir, inflow of cold snowmelt waters, and heat losses by evaporation. In spite of the rather low water temperatures, and consequently low vapor pressure, e_o, relatively high evaporation rates are maintained because of the dry air, as illustrated by low values of vapor pressure, e_a, as shown on figure 35. Wind speeds at Antero Reservoir, as shown on figure 36, are in about the same moderately high range as speeds measured at several other water-supply reservoirs.

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1967			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	7	July 25- Aug. 1	5.2	11.7	0.36	2.49	149.11	4.14	0.60
2	7	Aug. 1- Aug. 8	5.1	10.5	.32	2.11	132.48	3.25	.68
3	7	Aug. 8- Aug. 15	5.0	10.1	.30	2.09	126.11	2.97	.70
4	7	Aug. 15- Aug. 22	5.4	10.5	.33	2.34	141.54	3.28	.71
5	8	Aug. 22- Aug. 30	4.8	8.9	.25	2.02	122.19	3.53	.57
6	7	Aug. 30-Sept. 6	5.6	7.9	.26	1.83	111.08	2.67	.69
7	7	Sept. 6-Sept. 13	7.5	8.7	.38	2.69	163.37	3.18	.85
8	7	Sept. 13-Sept. 20	6.7	8.9	.35	2.46	149.47	2.94	.84
9	7	Sept. 20-Sept. 27	4.2	7.5	.19	1.30	78.91	2.84	.46
10	7	Sept. 27- Oct. 4	5.9	8.0	.28	1.95	118.37	3.68	.53
11	7	Oct. 4- Oct. 11	6.5	7.1	.27	1.91	115.94	2.21	.86
12	7	Oct. 11- Oct. 18	6.8	6.8	.27	1.91	115.94	2.57	.74
13	7	Oct. 18- Oct. 25	8.2	6.7	.32	2.27	137.79	2.92	.77
14	7	Oct. 25- Nov. 1	10.8	---	---	----	------	2.26	----
Record season	92	July 25- Oct. 25			0.299	27.47	1,662.30	37.92	
Pan season	99	July 25- Nov. 1						40.18	0.72

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1968			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
15	7	May 17- May 22	7.7	----	----	----	------	2.54	----
16	7	May 22- May 29	10.3	7.7	0.47	3.28	208.10	5.31	0.62
17	7	May 29- June 5	5.9	7.2	.25	1.75	110.56	4.98	.35
18	7	June 5- June 12	7.8	9.8	.45	3.16	199.82	4.90	.64
19	7	June 12- June 19	7.6	10.0	.45	3.14	199.41	6.45	.49
20	7	June 19- June 26	6.6	9.8	.38	2.67	170.29	6.05	.44
21	7	June 26- July 3	9.1	11.7	.63	4.40	280.63	7.80	.56
22	7	July 3- July 10	5.9	7.3	.25	1.78	113.69	3.56	.50
23	7	July 10- July 17	5.3	8.0	.25	1.75	111.72	4.50	.39
24	7	July 17- July 24	5.7	9.6	.32	2.26	144.42	4.34	.52
25	7	July 24- July 31	5.1	6.9	.21	1.45	92.70	2.84	.51
26	7	July 31- Aug. 7	4.6	7.8	.21	1.48	94.48	2.46	.60

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1968			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
27	7	Aug. 7- Aug. 14	4.9	6.9	0.20	1.40	89.63	2.46	0.57
28	7	Aug. 14- Aug. 21	9.5	11.4	.64	4.47	285.36	5.11	.87
29	7	Aug. 21- Aug. 28	6.8	10.1	.41	2.84	181.65	4.55	.62
30	7	Aug. 28-Sept. 4	6.1	9.2	.33	2.32	148.18	2.97	.78
31	7	Sept. 4-Sept. 11	5.6	9.8	.32	2.27	144.99	3.81	.60
32	7	Sept. 11-Sept. 18	7.7	9.0	.41	2.86	182.67	3.43	.83
33	7	Sept. 18-Sept. 25	6.9	7.6	.31	2.17	138.40	3.73	.58
34	7	Sept. 25- Oct. 2	5.6	7.4	.24	1.71	109.27	3.12	.55
35	7	Oct. 2- Oct. 9	6.6	6.6	.26	1.80	114.97	2.90	.62
36	7	Oct. 9- Oct. 16	7.4	5.4	.24	1.65	105.33	2.44	.68
37	7	Oct. 16- Oct. 23	7.7	6.7	.30	2.13	135.91	----	----
38	7	Oct. 23- Oct. 30	5.5	5.3	.17	1.20	76.72	----	----
Record season	161	May 22- Oct. 30			0.34	53.94	3,438.9		
Pan season	147	May 22- Oct. 16			0.34	50.61		87.71	0.58

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
39	7	May 14- May 21	5.6	7.1	0.23	1.64	104.89	3.96	0.41
40	7	May 21- May 28	6.0	7.8	.28	1.93	123.85	4.62	.42
41	7	May 28- June 4	7.6	9.5	.43	2.98	191.14	6.07	.49
42	7	June 4- June 11	6.9	8.3	.34	2.37	152.09	4.60	.52
43	7	June 11- June 18	6.1	7.7	.28	1.94	125.31	2.13	.91
44	8	June 18- June 26	8.8	7.2	.37	2.99	192.05	5.11	.59
45	6	June 26- July 2	9.0	7.5	.40	2.39	152.93	5.28	.45
46	7	July 2- July 9	6.5	7.8	.30	2.13	136.62	5.97	.36
47	7	July 9- July 16	4.7	7.9	.22	1.53	98.04	4.39	.35
48	7	July 16- July 23	---	---	----	----	------	4.06	----
49	7	July 23- July 30	---	---	----	----	------	4.62	----
50	7	July 30- Aug. 6	---	---	----	----	------	4.85	----

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
51	7	Aug. 6- Aug. 13	---	----	----	----	------	5.69	----
52	7	Aug. 13- Aug. 20	5.4	11.6	0.37	2.59	165.43	3.63	0.71
53	7	Aug. 20- Aug. 27	5.0	9.6	.28	1.98	126.64	3.81	.52
54	7	Aug. 27-Sept. 3	5.2	8.7	.27	1.87	119.32	3.43	.55
55	7	Sept. 3-Sept. 10	5.6	10.0	.33	2.31	147.40	3.78	.61
56	7	Sept. 10-Sept. 17	4.8	9.3	.26	1.84	117.52	2.46	.75
57	7	Sept. 17-Sept. 24	5.1	8.1	.24	1.71	109.42	2.34	.73
58	7	Sept. 24- Oct. 1	5.3	8.8	.28	1.93	123.21	3.38	.57
59	7	Oct. 1- Oct. 8	7.3	8.3	.36	2.50	160.35	2.11	1.18
60	8	Oct. 8- Oct. 16	6.6	----	----	----	------	----	----
61	6	Oct. 16- Oct. 22	5.7	----	----	----	------	----	----
Record season	119	May 14- July 16 Aug. 13- Oct. 8			0.31	36.63	2,346.21		
Pan season	147	May 14- July 16 Aug. 13- Oct. 8			0.31	36.63		67.77	0.54

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
62	7	June 3- June 10	7.4	7.6	0.33	2.32	140.62	4.67	0.50
63	7	June 10- June 17	8.9	7.3	.38	2.68	167.45	5.26	.51
64	7	June 17- June 24	6.1	7.5	.27	1.89	120.65	5.54	.34
65	7	June 24- July 1	6.8	9.9	.40	2.78	177.56	6.60	.42
66	7	July 1- July 8	5.0	11.3	.33	2.33	149.66	5.18	.45
67	7	July 8- July 15	4.4	10.9	.28	1.98	127.00	4.32	.46
68	7	July 15- July 22	5.4	12.5	.40	2.79	178.28	4.57	.61
69	7	July 22- July 29	5.6	10.6	.35	2.45	156.70	3.94	.62
70	7	July 29- Aug. 5	4.5	10.8	.29	2.01	128.44	4.75	.42
71	7	Aug. 5- Aug. 12	4.0	10.2	.24	1.69	108.25	6.20	.27

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
72	7	Aug. 12- Aug. 19	4.7	11.4	0.32	2.21	141.35	4.01	0.55
73	7	Aug. 19- Aug. 26	3.9	9.1	.21	1.47	93.80	3.35	.44
74	7	Aug. 26-Sept. 2	4.7	9.4	.26	1.82	116.19	3.61	.50
75	7	Sept. 2-Sept. 9	7.3	8.7	.37	2.62	167.10	3.73	.70
76	7	Sept. 9-Sept. 16	8.1	7.0	.33	2.34	149.38	3.81	.61
77	7	Sept. 16-Sept. 23	6.0	8.3	.29	2.06	131.64	4.04	.51
78	7	Sept. 23-Sept. 30	3.9	7.2	.17	1.16	74.09	1.50	.77
79	8	Sept. 30- Oct. 8	5.2	6.0	.18	1.47	93.80	2.84	.52
80	7	Oct. 8- Oct. 15	---	----	----	----	------	----	----
Record season	127	June 3- Oct. 8			0.30	38.07	2,421.96		
Pan season	127	June 3- Oct. 8			0.30	38.07		77.92	0.49

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
81	3.8	June 6- June 10	6.51	8.2	0.312	1.20	77.68	3.72	0.32
82	6.0	June 10- June 16	6.35	7.8	.293	1.76	114.4	4.83	.36
83	7.0	June 16- June 23	6.10	8.0	.287	2.01	130.7	5.72	.35
84	7.2	June 23- June 30	7.01	10.4	.431	3.09	200.3	8.53	.36
85	6.8	June 30- July 7	7.56	9.5	.424	2.88	186.8	6.15	.47
86	7.0	July 7- July 14	5.79	9.4	.320	2.24	145.6	6.84	.33
87	7.0	July 14- July 21	4.88	8.8	.251	1.75	114.2	4.84	.36
88	7.1	July 21- July 28	5.54	8.5	.277	1.96	127.8	4.61	.43
89	7.0	July 28- Aug. 4	5.71	8.6	.289	2.03	131.8	5.29	.38

Table 12.--*Summary of mass-transfer terms and pan evaporation for Antero Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
90	6.9	Aug. 4- Aug. 11	5.60	8.0	0.262	1.82	118.0	4.90	0.37
91	8.0	Aug. 11- Aug. 19	4.98	7.4	.216	1.73	112.2	5.33	.32
92	6.0	Aug. 19- Aug. 25	4.20	6.6	.163	.98	63.6	3.25	.30
93	7.0	Aug. 25-Sept. 1	4.02	7.8	.185	1.30	84.3	3.45	.38
94	7.0	Sept. 1-Sept. 8	7.33	10.3	.442	3.10	200.8	5.07	.61
95	7.0	Sept. 8-Sept. 15	4.85	9.7	.277	1.94	125.6	5.77	.34
96	7.1	Sept. 15-Sept. 22	5.26	8.5	.262	1.86	121.5	----	----
97	7.1	Sept. 22-Sept. 29	7.55	6.7	.297	2.11	137.0	----	----
Record season	115	June 6-Sept. 29			0.29	33.76	2,192.28		
Pan season	100.8	June 6-Sept. 15			0.30	29.79		78.30	0.38

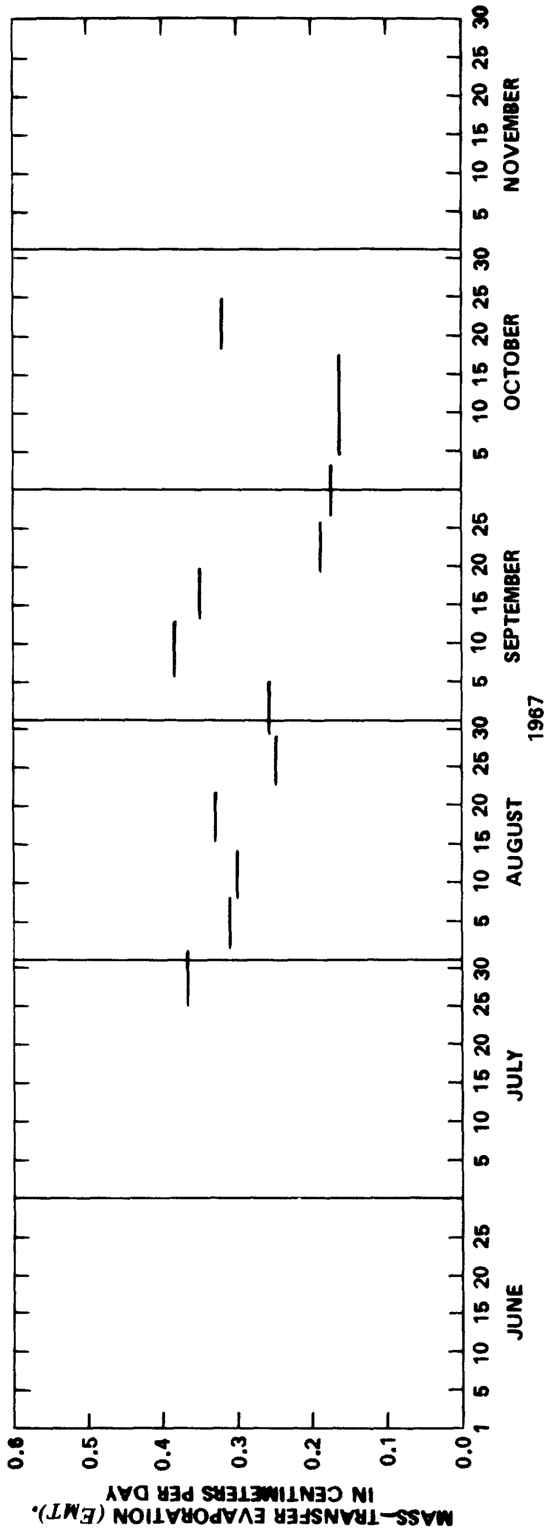

Figure 33.—Rates of mass-transfer evaporation, E_{MT}, from Antero Reservoir for the 1967–71 record seasons.

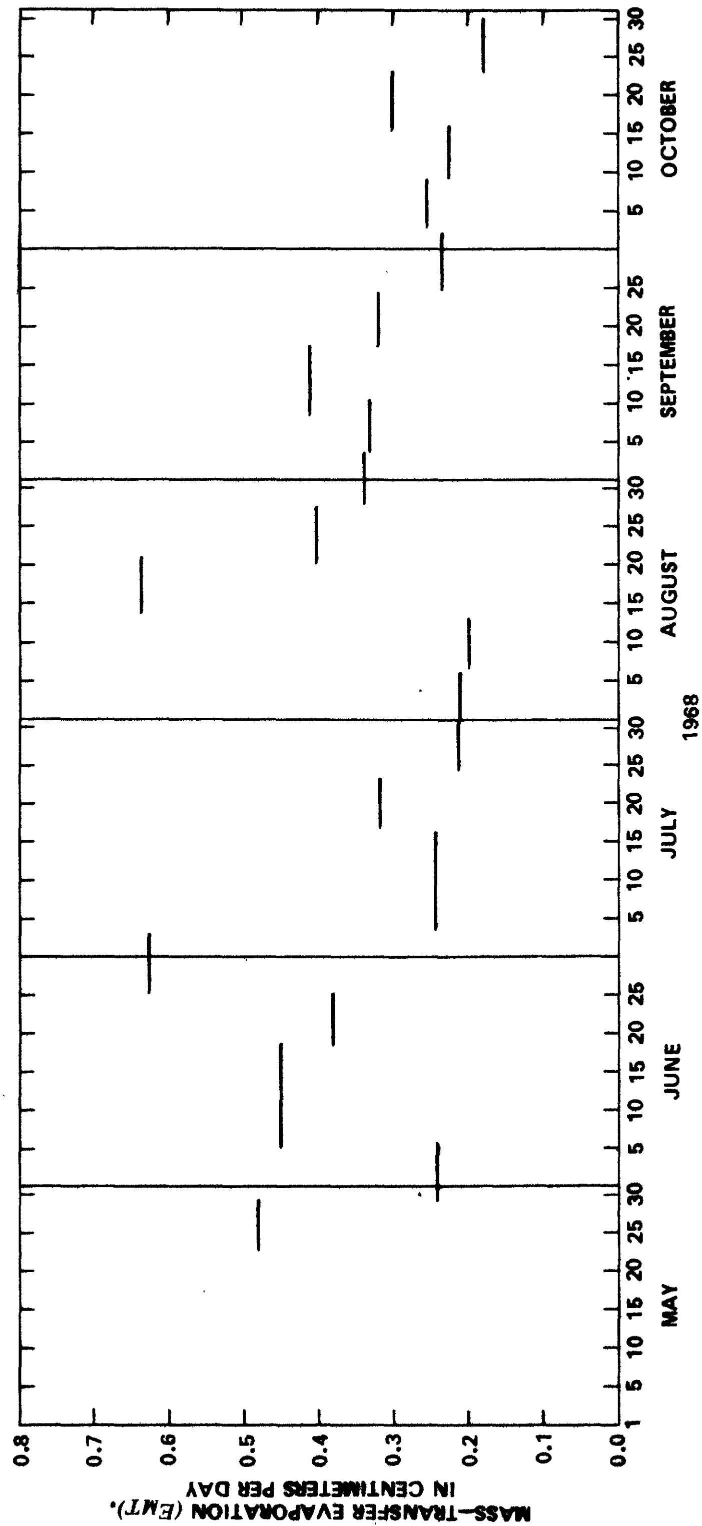

Figure 33.—Rates of mass-transfer evaporation, E_{MT}, from Antero Reservoir for the 1967–71 record seasons—Continued.

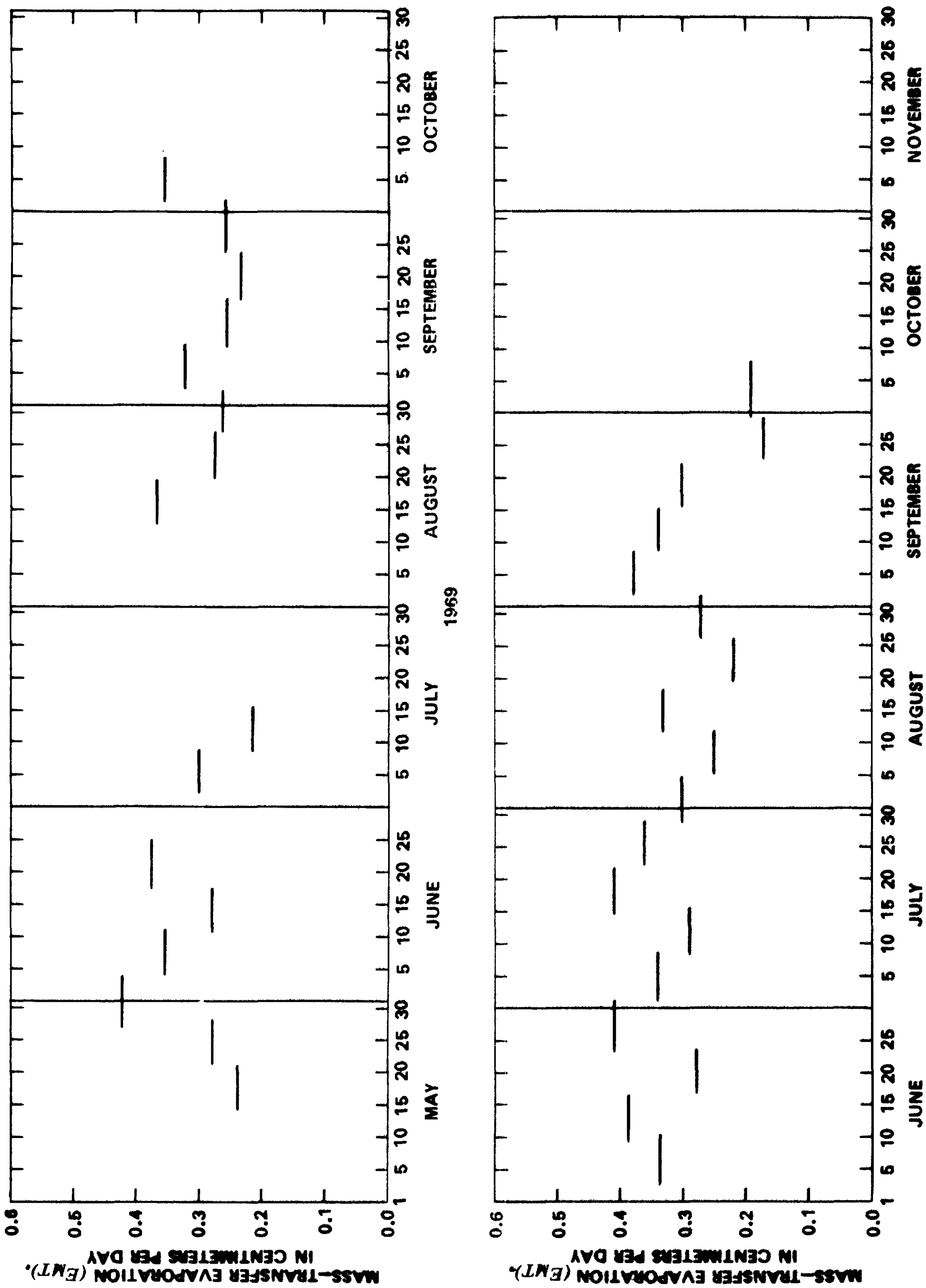

Figure 33.—Rates of mass-transfer evaporation, E_{MT}, from Antero Reservoir for the 1967–71 record seasons—Continued.

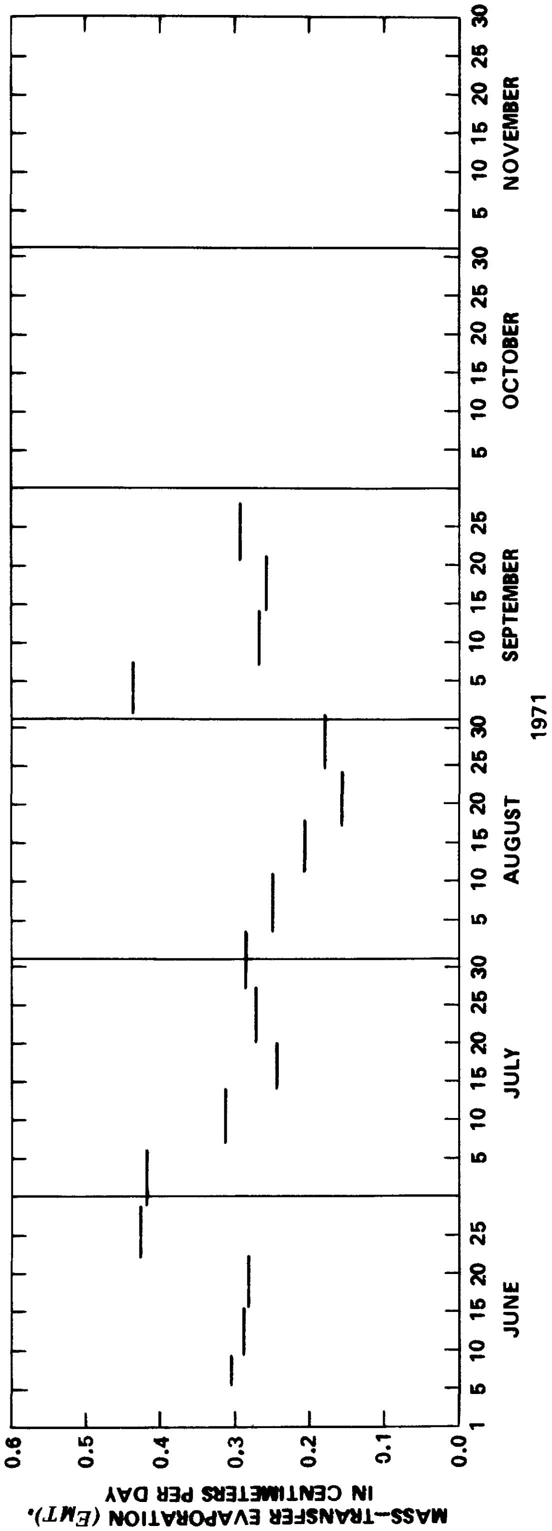

Figure 33.—Rates of mass-transfer evaporation, E_{MT}, from Antero Reservoir for the 1967–71 record seasons—Continued.

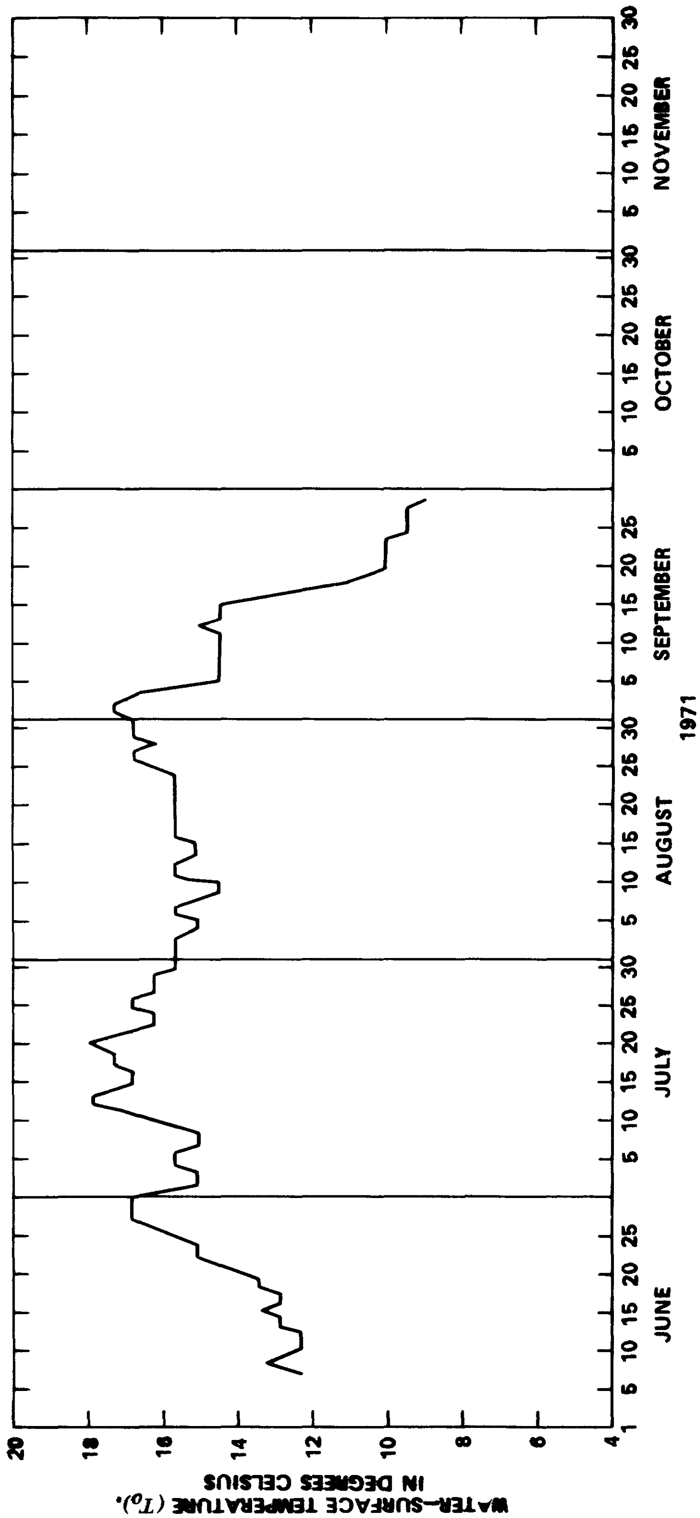

Figure 34.—Time graph of water-surface temperature, T_O, of Antero Reservoir.

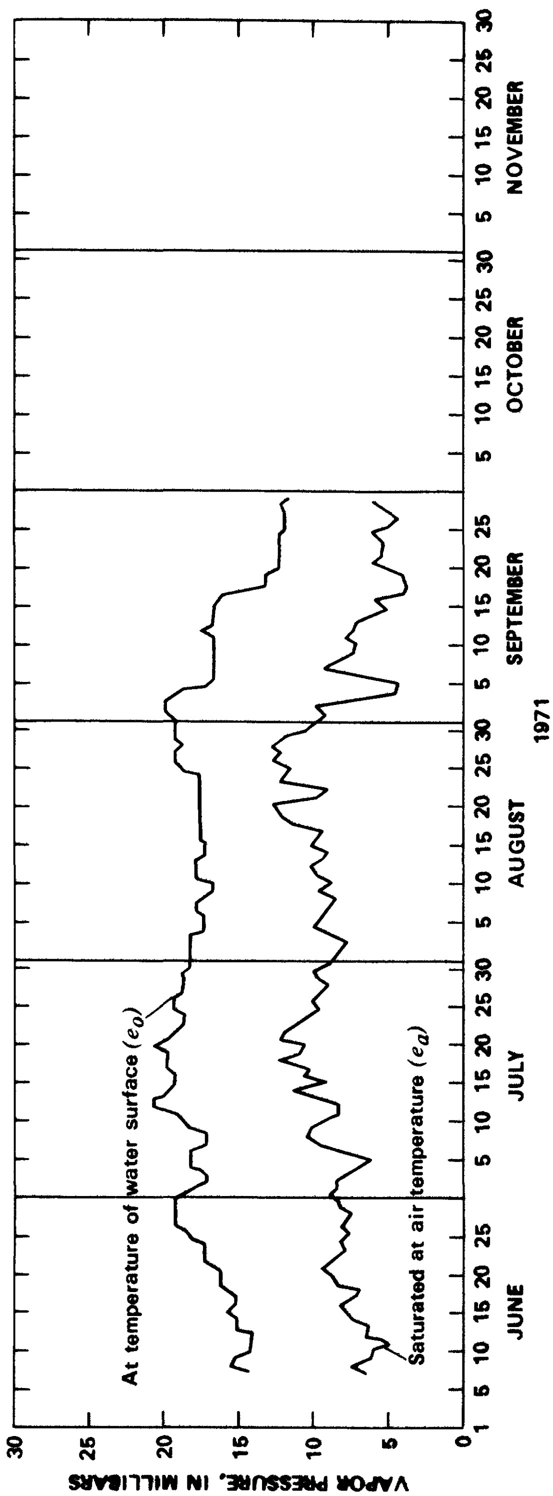

Figure 35.—Time graph of vapor pressures, e_o and e_a, at Antero Reservoir.

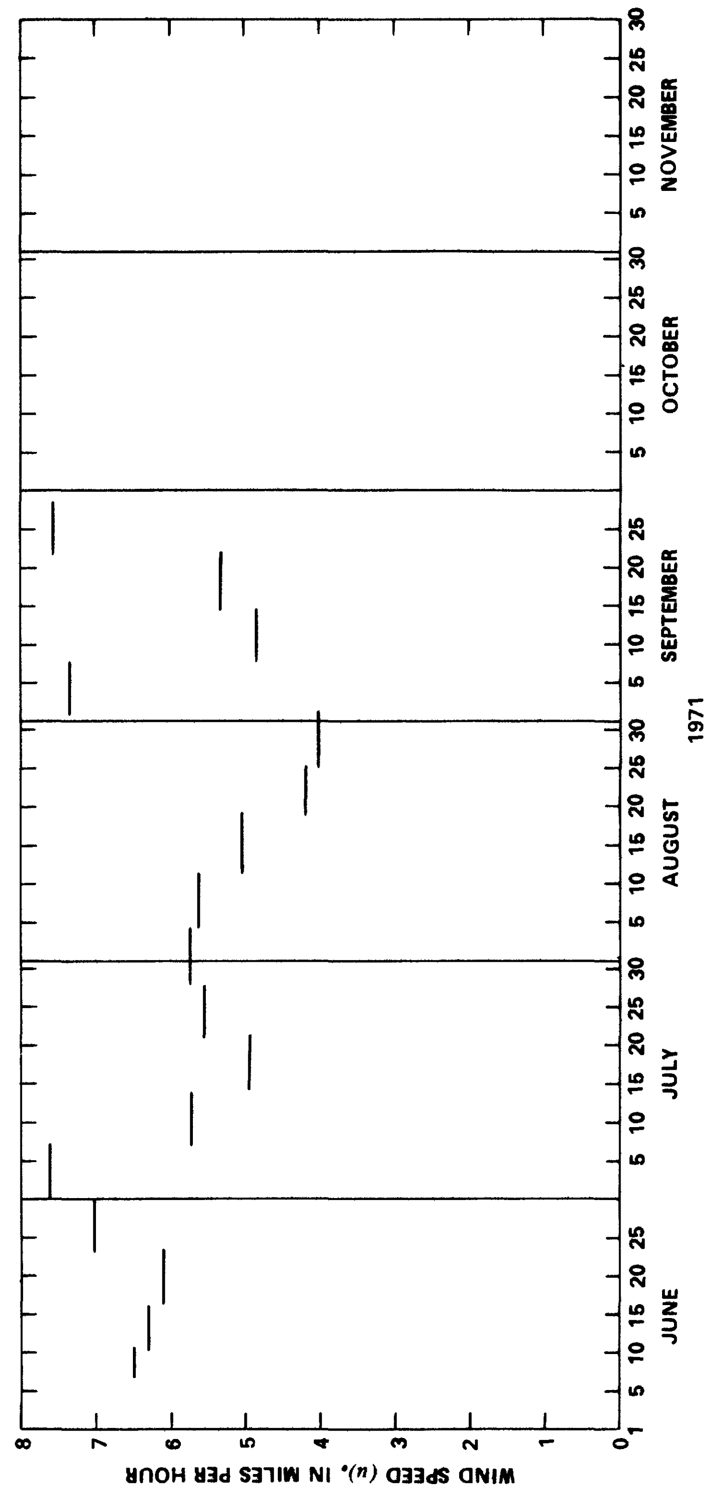

Figure 36.—Time graph of wind speeds, *u*, at Antero Reservoir.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Antero Reservoir is listed in table 12 with the mass-transfer evaporation.

Pan evaporation data and ratios of reservoir to pan evaporation are listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratios also are listed and, as can be seen, the ratios differ substantially from season to season, as well as some being significantly different from the common 0.7 coefficient. The ratios for Antero Reservoir are varied and have been calibrated against mass-transfer evaporation computed using Harbeck's equation (equation 8 of this report). In the event that it is determined that the pan method needs to be used to determine evaporation at this facility, the pan ratio needs to be calibrated against a more reliable method of evaporation determination, such as the energy-budget method.

EVAPORATION FROM CHEESMAN RESERVOIR

Cheesman Reservoir is located 40 mi (64.4 km) southwest of Denver, and occupies the farthest downstream position of the reservoirs in the South Platte River system. It also is the oldest reservoir in the system, having been completed in 1905.

Cheesman's masonry arch dam is 231 ft (70.4 m) high and is set into the walls of a narrow canyon formed by the South Platte River. When full, the reservoir holds 79,064 acre-ft (97.5 hm^3) of water, with the surface 6,842 ft (2,085.4 m) above sea level, and has a surface area of 871 acres (3.52 km^2).

Records of evaporation from Cheesman Reservoir were computed by the mass-transfer and pan methods for 1967-73. The mass-transfer calculations from existing and future data can be improved by N-value calibration from future energy-budget studies. The hygrothermograph and standard class-A pan were located near the dam. Surface temperature was recorded and average wind speed was measured with instruments on a raft anchored near the center of the reservoir.

Mass-Transfer Records

No independent records of evaporation were available to calibrate the mass-transfer coefficient, N, for Cheesman Reservoir. Consequently, as was done in the case of Antero Reservoir, values of N were estimated using Harbeck's equation (equation 8 in this report).

For 1967-70, a uniform value of N = 0.0061 was used in evaporation computation. During the last 3 years, 1971-73, different values of N were determined for each computation period by means of a computer program that solved equation 8 using the mean surface area during the period. However, surface area of the reservoir did not vary greatly, and consequently computed values of N varied only slightly, within the range from 0.0061 to 0.0062.

Data on evaporation from Cheesman Reservoir, as computed by the mass-transfer method for 1967-73, are summarized in table 13. Most rates shown are averages over the 7-day periods between times of dial readings from the anemometer. Rates for the 7 years of record also are shown graphically in the evaporation hydrographs on figure 37. Evaporation rates for the 7-day periods generally range from slightly less than 0.2 to 0.4 or 0.5 cm/d.

Data on meteorologic conditions during the 1973 record season are included as examples on figures 38, 39, and 40. Temperature data on figure 38 illustrate that the reservoir surface warmed rapidly in the spring to a temperature of 15°C by late May. A similar pattern is shown on figure 39 by the graph of saturation vapor pressure, e_o, corresponding to temperature of the surface. As is shown by the data on figure 39, values of the vapor-pressure difference, e_o-e_a, generally were in the range of from 6 to 12 millibars. Wind speeds, as illustrated on figure 40, usually were in the range of about 3.5 to 6 mi/h (1.56 to 2.68 m/s) most of the time, but occasionally were considerably greater.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Cheesman Reservoir is listed in table 13 with the mass-transfer evaporation.

This evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratios also are listed and, as can be seen, the ratios differ little from season to season. However, they are significantly different from the common 0.7 coefficient. The ratios for Cheesman Reservoir have been calibrated against mass-transfer evaporation as computed using Harbeck's N values. In the event that it is determined that the pan method needs to be used to determine evaporation at this facility, the pan ratio needs to be calibrated against a more reliable method of evaporation determination, such as the energy-budget method.

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1967			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	6	May 9- May 15	5.6	6.6	0.23	1.35	22.68	3.02	0.45
2	7	May 15- May 22	4.2	7.0	.18	1.26	21.02	3.40	.37
3	7	May 22- May 29	3.8	8.1	.19	1.31	21.20	3.05	.43
4	7	May 29- June 5	5.4	7.5	.25	1.73	27.82	3.81	.46
5	7	June 5- June 12	5.4	9.4	.31	2.17	34.73	3.99	.54
6	7	June 12- June 19	5.1	8.8	.27	1.92	30.46	3.20	.60
7	7	June 19- June 26	4.8	8.4	.25	1.72	27.26	2.92	.59
8	7	June 26- July 3	4.4	9.6	.26	1.80	29.08	4.42	.41
9	7	July 3- July 10	4.4	9.5	.25	1.78	29.00	4.32	.41
10	7	July 10- July 17	4.3	12.9	.34	2.37	39.13	3.71	.64
11	7	July 17- July 24	3.5	13.9	.30	2.08	35.44	3.73	.56
12	7	July 24- July 31	4.2	12.6	.32	2.26	39.82	4.14	.55
13	7	July 31- Aug. 7	3.6	12.6	.28	1.94	34.08	3.20	.61

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1967			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
14	7	Aug. 7- Aug. 14	4.1	10.9	0.27	1.91	33.25	3.07	0.62
15	7	Aug. 14- Aug. 21	4.0	13.5	.33	2.31	40.08	3.38	.68
16	9	Aug. 21- Aug. 30	3.7	12.4	.28	2.52	41.75	4.50	.56
17	7	Aug. 30-Sept. 6	4.4	10.4	.28	1.95	31.00	3.12	.63
18	7	Sept. 6-Sept. 13	5.7	11.8	.41	2.87	45.49	3.94	.73
19	7	Sept. 13-Sept. 20	4.4	10.8	.29	2.03	32.21	2.77	.73
20	7	Sept. 20-Sept. 27	3.7	10.0	.23	1.58	25.50	2.87	.55
21	9	Sept. 27- Oct. 6	4.7	9.6	.28	2.48	40.95	4.42	.56
22	5	Oct. 6- Oct. 11	4.0	9.9	.24	1.21	20.41	1.40	.86
23	7	Oct. 11- Oct. 18	4.0	10.8	.26	1.84	31.57	1.96	.94
24	7	Oct. 18- Oct. 25	4.3	10.3	.27	1.89	32.66	2.39	.79
25	7	Oct. 25- Nov. 1	4.6	9.5	.27	1.87	32.58	----	----
Record season	176	May 9- Nov. 1			0.27	48.15	799.17		
Pan season	176	May 9- Nov. 1			0.27	48.15		87.76	0.55

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

No.	Period: Length (days)	Period: Dates 1968	$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method: Centimeters per day	Centimeters per period	Acre-feet per period	Pan evaporation: Centimeters per period	Ratio of reservoir to pan evaporation
26	6	May 16- May 22	4.9	6.2	0.19	1.11	25.11	2.21	0.50
27	7	May 22- May 29	5.0	6.8	.21	1.45	32.97	3.89	.37
28	7	May 29- June 5	4.4	8.5	.23	1.60	36.54	4.52	.35
29	8	June 5- June 13	5.3	11.4	.37	2.95	67.41	5.94	.50
30	6	June 13- June 19	5.0	11.2	.34	2.05	46.94	4.83	.42
31	7	June 19- June 26	5.1	12.1	.38	2.64	59.81	5.72	.46
32	8	June 26- July 4	5.9	13.6	.49	3.92	87.20	7.47	.52
33	6	July 4- July 10	4.3	10.8	.28	1.70	36.89	3.38	.50
34	7	July 10- July 17	3.5	10.3	.22	1.54	32.94	3.61	.43
35	7	July 17- July 24	4.3	10.2	.27	1.87	39.04	4.57	.41
36	7	July 24- July 31	3.4	9.5	.20	1.38	28.23	2.82	.49
37	7	July 31- Aug. 7	3.5	10.1	.22	1.51	30.66	2.62	.58
38	7	Aug. 7- Aug. 14	3.8	9.3	.22	1.51	30.56	2.95	.51

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

No.	Period: Length (days)	Period: Dates 1968	$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method: Centimeters per day	Centimeters per period	Acre-feet per period	Pan evaporation: Centimeters per period	Ratio of reservoir to pan evaporation
39	7	Aug. 14- Aug. 21	6.6	12.5	0.50	3.52	72.41	5.46	0.64
40	7	Aug. 21- Aug. 28	5.2	11.8	.37	2.62	54.55	5.79	.45
41	7	Aug. 28-Sept. 4	4.2	11.1	.28	1.99	40.67	3.15	.63
42	7	Sept. 4-Sept. 11	4.3	11.7	.31	2.15	43.87	4.50	.48
43	7	Sept. 11-Sept. 18	4.8	10.8	.32	2.21	45.06	3.28	.67
44	8	Sept. 18-Sept. 26	5.0	10.9	.33	2.66	51.31	3.76	.71
45	6	Sept. 26- Oct. 2	4.5	10.1	.28	1.66	31.72	2.57	.65
46	7	Oct. 2- Oct. 9	4.1	9.5	.24	1.66	31.15	2.51	.66
47	14	Oct. 9- Oct. 23	4.4	9.6	.26	3.61	67.21	4.62	.78
48	8	Oct. 23- Oct. 31	3.7	9.0	.20	1.63	30.30	2.34	.70
Record season	168	May 16- Oct. 31			0.29	48.95	1,022.55		
Pan season	168	May 16- Oct. 31			0.29	48.95		92.51	0.53

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
49	7	May 14- May 21	4.2	5.3	0.14	0.95	24.27	3.05	0.31
50	7	May 21- May 28	4.6	6.5	.18	1.28	34.38	3.25	.39
51	7	May 28- June 4	4.8	7.7	.23	1.58	44.53	3.73	.42
52	7	June 4- June 11	5.0	6.2	.19	1.32	38.01	3.18	.42
53	7	June 11- June 18	4.4	5.7	.15	1.07	30.89	1.45	.74
54	8	June 18- June 26	6.9	6.2	.26	2.09	60.42	3.99	.52
55	6	June 26- July 2	6.8	6.4	.27	1.59	45.82	5.11	.31
56	7	July 2- July 9	5.4	7.3	.24	1.68	48.37	5.18	.32
57	7	July 9- July 16	4.2	6.3	.16	1.13	32.49	3.96	.29
58	7	July 16- July 23	4.0	6.6	.16	1.13	32.32	3.05	.37
59	7	July 23- July 30	3.7	7.2	.16	1.14	32.76	3.53	.32
60	7	July 30- Aug. 6	4.3	10.2	.27	1.87	53.29	3.56	.53

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
61	7	Aug. 6- Aug. 13	5.0	14.4	0.44	3.07	86.58	5.49	0.56
62	7	Aug. 13- Aug. 20	3.7	12.6	.28	1.99	55.46	3.58	.56
63	7	Aug. 20- Aug. 27	4.0	11.0	.27	1.88	52.09	3.23	.58
64	7	Aug. 27-Sept. 3	3.7	11.9	.27	1.88	51.99	3.30	.57
65	7	Sept. 3-Sept. 10	4.1	12.8	.32	2.24	61.40	3.18	.70
66	7	Sept. 10-Sept. 17	3.6	11.7	.26	1.80	47.95	2.26	.80
67	7	Sept. 17-Sept. 24	4.4	11.3	.30	2.12	55.30	2.54	.83
68	7	Sept. 24- Oct. 1	3.9	12.4	.29	2.06	53.63	3.58	.58
69	7	Oct. 1- Oct. 8	4.5	11.4	.31	2.19	56.80	2.62	.84
70	7	Oct. 8- Oct. 15	5.5	9.7	.33	2.28	60.81	----	----
71	7	Oct. 15- Oct. 22	4.7	7.4	.21	1.49	41.14	----	----
Record season	161	May 14- Oct. 22			0.25	39.84	1,100.70		
Pan season	147	May 14- Oct. 8			0.25	36.07		72.82	0.50

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
72	8	June 2- June 10	5.1	7.5	0.23	1.87	53.66	4.45	0.42
73	7	June 10- June 17	6.1	9.2	.34	2.40	69.01	4.17	.58
74	7	June 17- June 24	4.3	8.4	.22	1.54	44.16	3.96	.39
75	7	June 24- July 1	5.5	11.4	.38	2.68	77.06	5.94	.45
76	7	July 1- July 8	3.9	11.1	.26	1.85	52.98	4.90	.38
77	7	July 8- July 15	4.0	10.8	.26	1.84	52.80	4.80	.38
78	7	July 15- July 22	3.9	11.6	.28	1.93	54.54	3.89	.50
79	7	July 22- July 29	4.1	11.6	.29	2.03	56.85	4.17	.49
80	7	July 29- Aug. 5	3.5	12.9	.28	1.93	53.19	4.75	.41
81	7	Aug. 5- Aug. 12	3.4	12.8	.27	1.86	51.11	3.66	.51

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
82	6	Aug. 12- Aug. 18	3.5	14.4	0.31	1.84	50.38	3.07	0.60
83	7	Aug. 18- Aug. 25	3.4	11.7	.24	1.70	46.48	3.00	.57
84	7	Aug. 25-Sept. 1	3.2	11.2	.22	1.53	41.80	4.55	.34
85	7	Sept. 1-Sept. 8	5.1	13.2	.41	2.87	78.36	3.76	.76
86	7	Sept. 8-Sept. 15	6.9	11.9	.50	3.51	95.46	4.19	.84
87	9	Sept. 15-Sept. 24	5.4	11.9	.39	3.53	95.66	5.33	.66
88	5	Sept. 24-Sept. 29	4.2	11.9	.30	1.52	41.34	1.35	1.13
89	7	Sept. 29- Oct. 6	3.5	10.1	.22	1.51	41.46	2.79	.54
90	7	Oct. 6- Oct. 13	4.4	10.0	.27	1.88	52.06	.81	2.33
91	7	Oct. 13- Oct. 20	3.4	----	----	----	------	----	----
Record season	133	June 2- Oct. 13			0.30	39.82	1,108.36		
Pan season	133	June 2- Oct. 13			0.30	39.82		73.54	0.54

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_0^{\sim}-e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
92	6.9	May 26- June 2	6.26	8.3	0.319	2.19	62.60	----	----
93	6.8	June 2- June 9	5.65	9.6	.331	2.26	64.68	5.18	0.44
94	7.0	June 9- June 16	4.29	8.6	.225	1.57	44.64	3.23	.49
95	7.0	June 16- June 23	4.64	9.5	.270	1.90	53.93	4.80	.40
96	7.0	June 23- June 30	5.16	11.5	.363	2.53	72.02	5.66	.45
97	7.0	June 30- July 7	5.28	11.4	.367	2.57	73.68	3.78	.68
98	7.0	July 7- July 14	3.99	10.5	.256	1.79	51.50	4.29	.42
99	7.0	July 14- July 21	3.70	9.1	.206	1.45	41.66	4.11	.35
100	7.0	July 21- July 28	4.11	8.8	.222	1.55	44.51	3.45	.45
101	7.1	July 28- Aug. 4	4.42	9.8	.264	1.88	53.92	3.66	.51

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
102	6.9	Aug. 4- Aug. 11	4.25	10.7	0.279	1.93	55.30	4.34	0.44
103	7.0	Aug. 11- Aug. 18	4.02	10.4	.256	1.79	51.47	4.14	.43
104	7.0	Aug. 18- Aug. 25	3.52	9.6	.206	1.45	41.53	3.56	.41
105	7.0	Aug. 25-Sept. 1	3.40	9.3	.194	1.36	39.05	2.44	.56
106	7.0	Sept. 1-Sept. 8	5.42	12.2	.406	2.84	81.62	5.38	.53
107	7.0	Sept. 8-Sept. 15	3.65	11.1	.247	1.72	49.33	4.11	.42
108	7.2	Sept. 15-Sept. 22	4.37	10.8	.290	2.07	59.49	1.42	1.46
109	7.9	Sept. 22-Sept. 30	7.33	8.2	.370	2.92	83.64	4.85	.60
110	6.1	Sept. 30- Oct. 6	6.44	8.8	.345	2.11	60.57	2.87	.74
111	6.9	Oct. 6- Oct. 13	3.62	7.4	.164	1.13	32.47	2.34	.48
112	7.1	Oct. 13- Oct. 20	6.06	8.0	.279	2.10	60.21	2.51	.84
Record season	146.9	May 26- Oct. 20			0.28	41.11	1,177.82		
Pan season	140.0	June 2- Oct. 20			0.28	38.92		76.12	0.51

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
113	6.7	May 31- June 7	4.08	8.2	0.206	1.38	35.35	----	----
114	8.0	June 7- June 15	3.61	9.5	.210	1.68	43.87	----	----
115	7.0	June 15- June 22	5.63	9.8	.339	2.38	62.58	----	----
116	7.1	June 22- June 29	4.66	11.7	.335	2.37	62.00	----	----
117	6.9	June 29- July 6	4.92	9.8	.295	2.04	52.75	----	----
118	7.0	July 6- July 13	3.88	9.8	.234	1.64	42.31	4.11	0.40
119	7.0	July 13- July 20	6.38	9.4	.368	2.59	66.56	4.83	.54
120	7.0	July 20- July 27	4.40	9.7	.262	1.82	46.84	4.95	.37
121	7.0	July 27- Aug. 3	4.30	10.3	.272	1.91	48.87	5.38	.36
122	7.0	Aug. 3- Aug. 10	3.74	11.1	.256	1.80	45.81	4.01	.45
123	7.0	Aug. 10- Aug. 17	3.29	10.1	.206	1.44	36.06	4.22	.34

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
124	7.1	Aug. 17- Aug. 24	3.86	11.3	0.268	1.90	46.91	2.90	0.66
125	6.9	Aug. 24- Aug. 31	3.40	9.3	.195	1.35	33.42	2.24	.60
126	7.0	Aug. 31-Sept. 7	4.32	9.3	.249	1.75	43.52	2.74	.64
127	7.0	Sept. 7-Sept. 14	4.41	8.3	.226	1.57	38.82	2.95	.53
128	7.0	Sept. 14-Sept. 21	4.61	11.0	.313	2.19	53.11	3.76	.58
129	7.0	Sept. 21-Sept. 28	7.32	10.7	.483	3.38	81.63	4.04	.84
130	7.0	Sept. 28- Oct. 5	4.73	9.9	.292	2.05	47.90	3.73	.55
131	7.0	Oct. 5- Oct. 12	4.40	9.1	.246	1.73	39.59	2.24	.77
132	7.0	Oct. 12- Oct. 19	4.55	8.2	.232	1.63	36.41	2.34	.70
133	6.2	Oct. 19- Oct. 25	4.84	8.8	.264	1.64	36.41	1.09	1.50
Record season	146.9	May 31- Oct. 25			0.274	40.23	1,000.72		
Pan season	111.2	July 6- Oct. 25			0.273	30.38		55.53	0.55

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
134	7.0	May 23- May 30	5.89	10.2	0.369	2.58	72.11	----	----
135	7.0	May 30- June 6	3.74	9.4	.215	1.50	42.92	----	----
136	6.8	June 6- June 13	3.72	7.6	.172	1.17	33.54	4.60	0.25
137	7.1	June 13- June 20	8.54	11.1	.579	4.09	117.3	6.99	.59
138	6.9	June 20- June 27	3.89	9.1	.216	1.50	43.00	5.79	.26
139	7.0	June 27- July 4	4.14	10.4	.264	1.86	53.21	5.94	.31
140	7.3	July 4- July 11	4.21	12.1	.312	2.26	64.80	5.54	.41
141	6.8	July 11- July 18	3.91	9.7	.232	1.57	44.65	4.55	.35
142	7.0	July 18- July 25	4.62	10.1	.288	2.01	55.75	4.70	.43
143	7.0	July 25- Aug. 1	3.65	9.9	.221	1.55	43.44	4.70	.33
144	7.0	Aug. 1- Aug. 8	3.75	7.0	.160	1.11	31.95	3.56	.31
145	7.0	Aug. 8- Aug. 15	3.45	8.9	.188	1.32	37.42	4.17	.32
146	7.0	Aug. 15- Aug. 22	3.77	10.0	.230	1.61	45.47	4.90	.33

Table 13.--*Summary of mass-transfer terms and pan evaporation for Cheesman Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
147	7.0	Aug. 22- Aug. 29	5.42	10.1	0.336	2.36	62.85	5.18	0.46
148	7.0	Aug. 29-Sept. 5	4.96	10.3	.315	2.21	57.23	4.52	.49
149	7.0	Sept. 5-Sept. 12	4.93	8.2	.248	1.73	43.74	4.62	.37
150	7.0	Sept. 12-Sept. 19	4.49	9.8	.273	1.91	47.85	4.01	.48
151	7.0	Sept. 19-Sept. 26	6.75	9.0	.375	2.63	64.29	7.54	.35
152	7.0	Sept. 26- Oct. 3	3.78	9.8	.229	1.60	38.80	7.62	.21
153	7.0	Oct. 3- Oct. 10	5.65	8.6	.300	2.10	51.46	3.84	.55
154	7.2	Oct. 10- Oct. 17	4.08	8.3	.209	1.50	36.42	3.56	.42
155	6.8	Oct. 17- Oct. 24	4.23	7.7	.200	1.37	32.95	3.02	.45
156	7.0	Oct. 24- Oct. 31	4.40	8.6	.233	1.64	39.45	2.69	.61
157	7.0	Oct. 31- Nov. 7	7.02	8.4	.364	2.55	60.96	2.24	1.14
158	7.0	Nov. 7- Nov. 14	6.16	5.6	.213	1.49	35.80	3.00	.50
159	8.3	Nov. 14- Nov. 22	6.75	7.6	.316	2.63	62.16	2.72	.97
160	6.7	Nov. 22- Nov. 29	5.43	7.1	.239	1.61	37.60	----	----
Record season	189.9	May 23- Nov. 29			0.263	49.85	1,357.12		
Pan season	169.2	June 6- Nov. 22			0.261	44.16		110.00	0.40

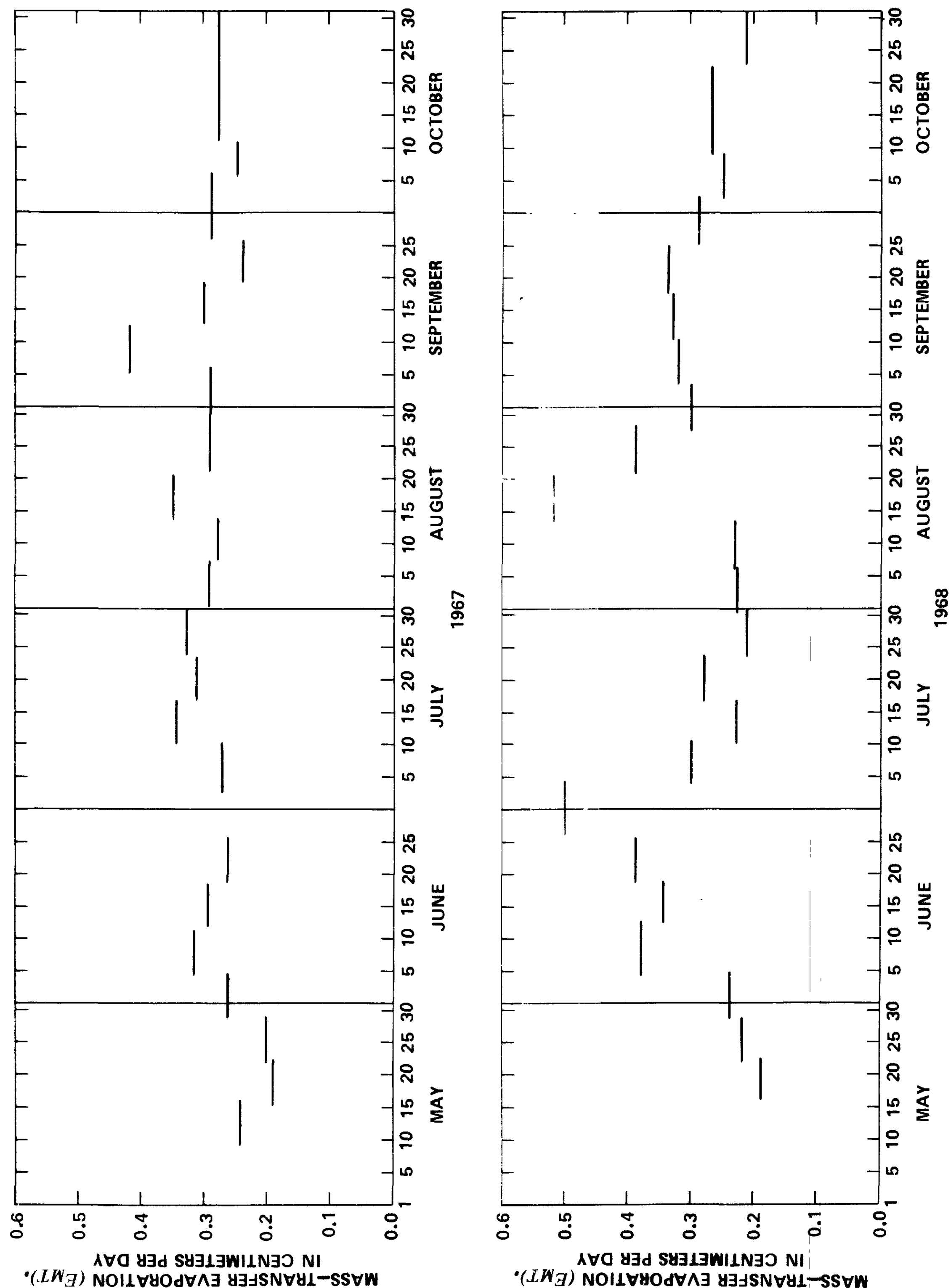

Figure 37.—Rates of mass-transfer evaporation, E_{MT}, from Cheesman Reservoir for the 1967–73 record seasons.

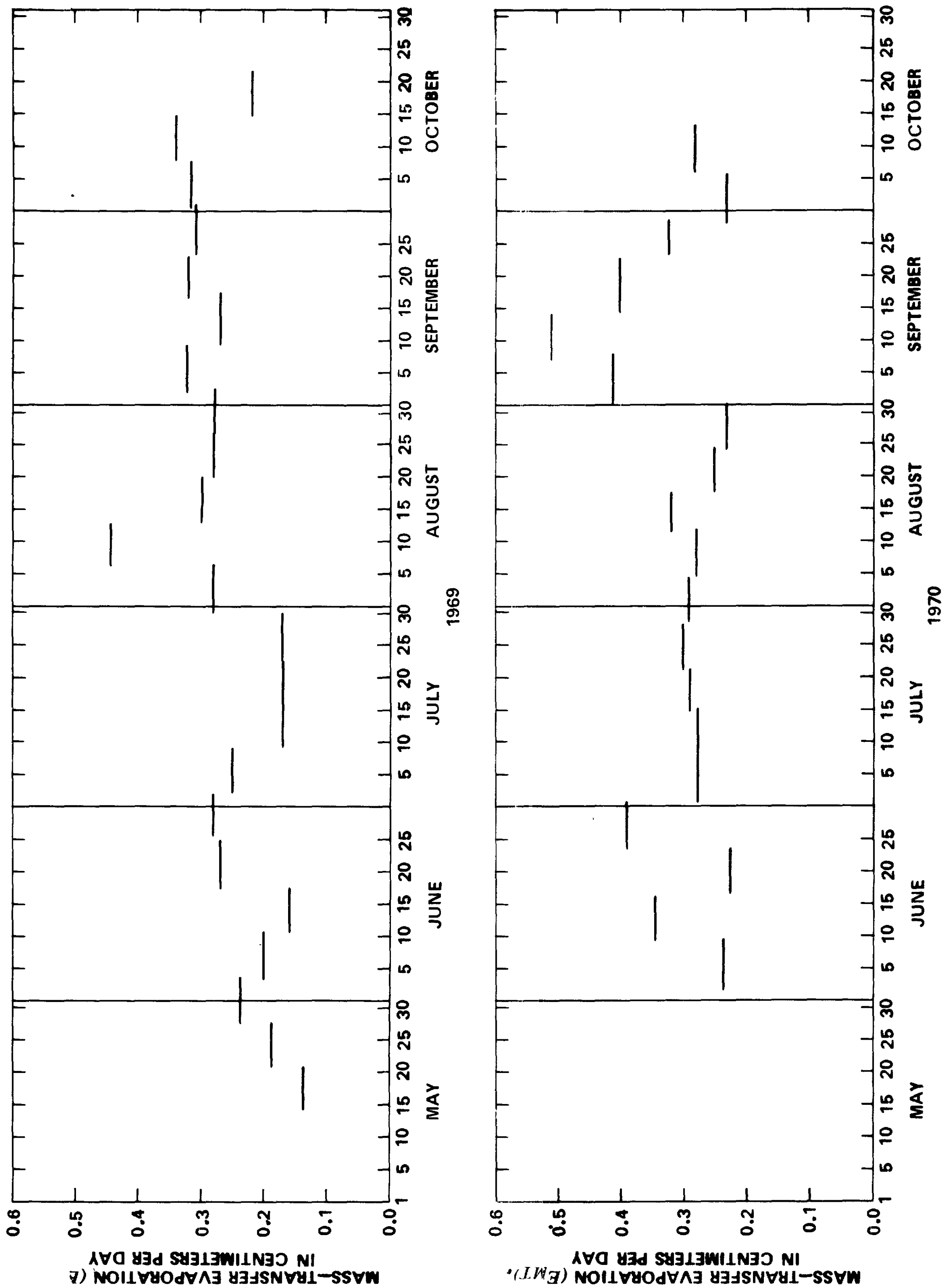

Figure 37.—Rates of mass–transfer evaporation, E_{MT}, from Cheesman Reservoir for the 1967–73 record seasons—Continued.

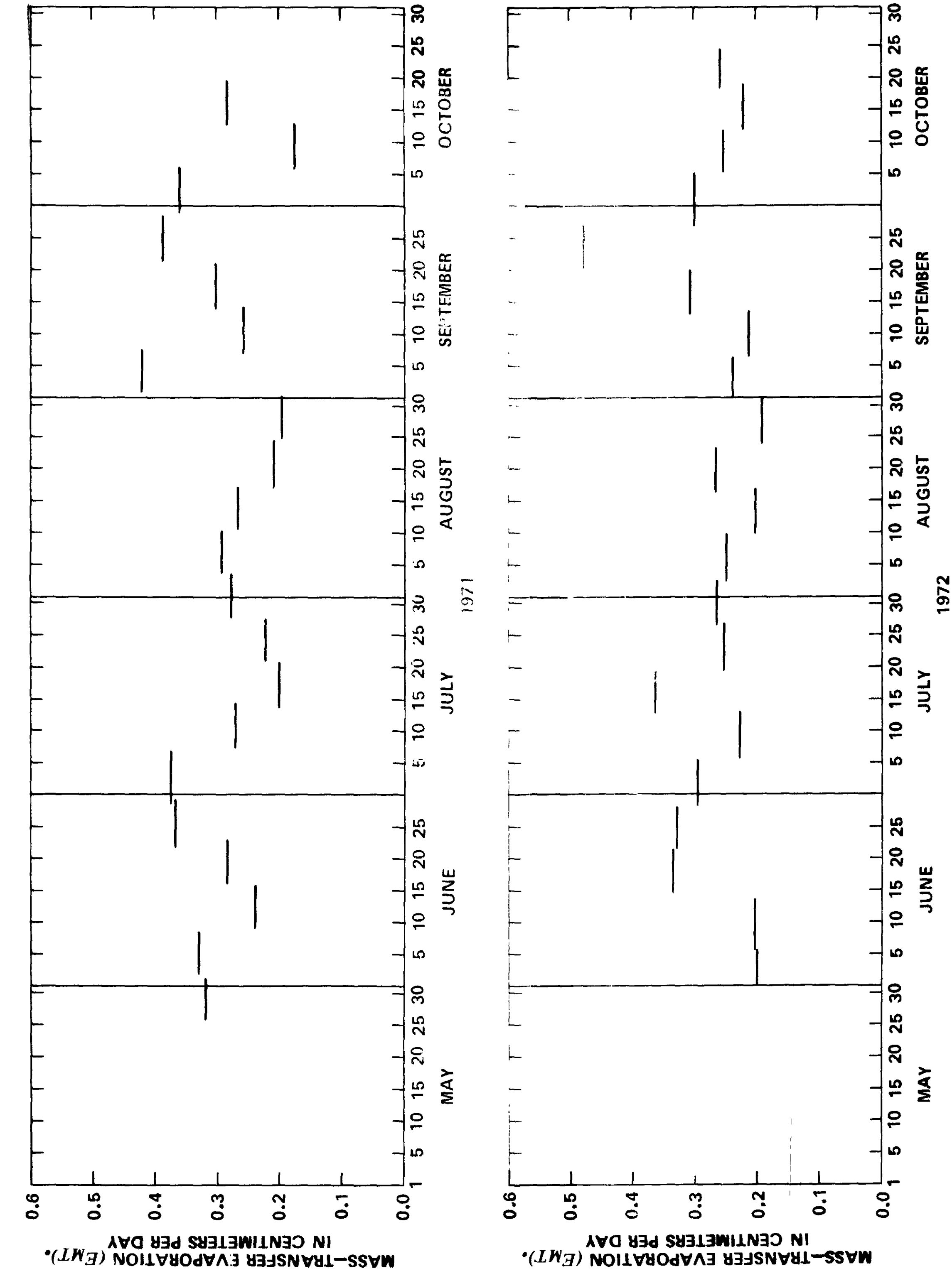

Figure 37.—Rates of mass-transfer evaporation, E_{MT}, from Cheesman Reservoir for the 1967–73 record seasons—Continued.

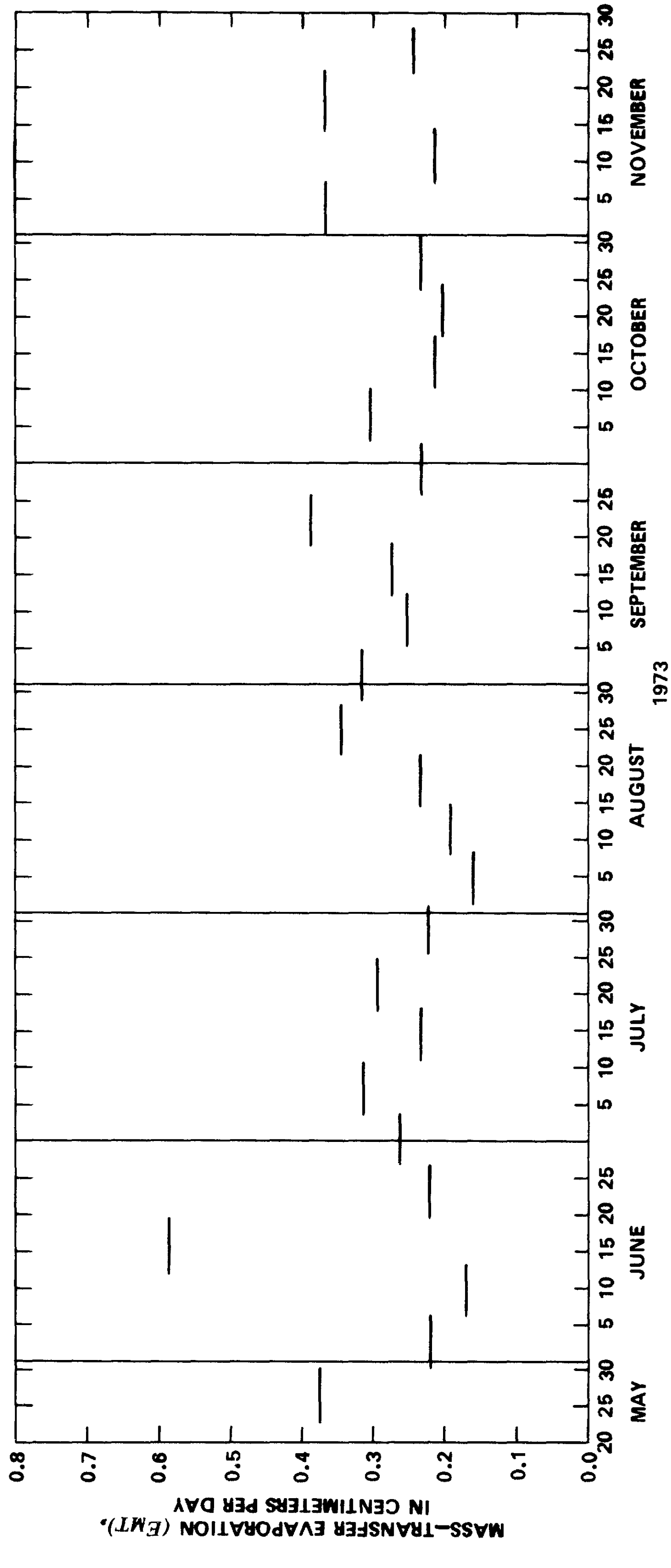

Figure 37.—Rates of mass-transfer evaporation, E_{MT}, from Cheesman Reservoir for the 1967–73 record seasons—Continued.

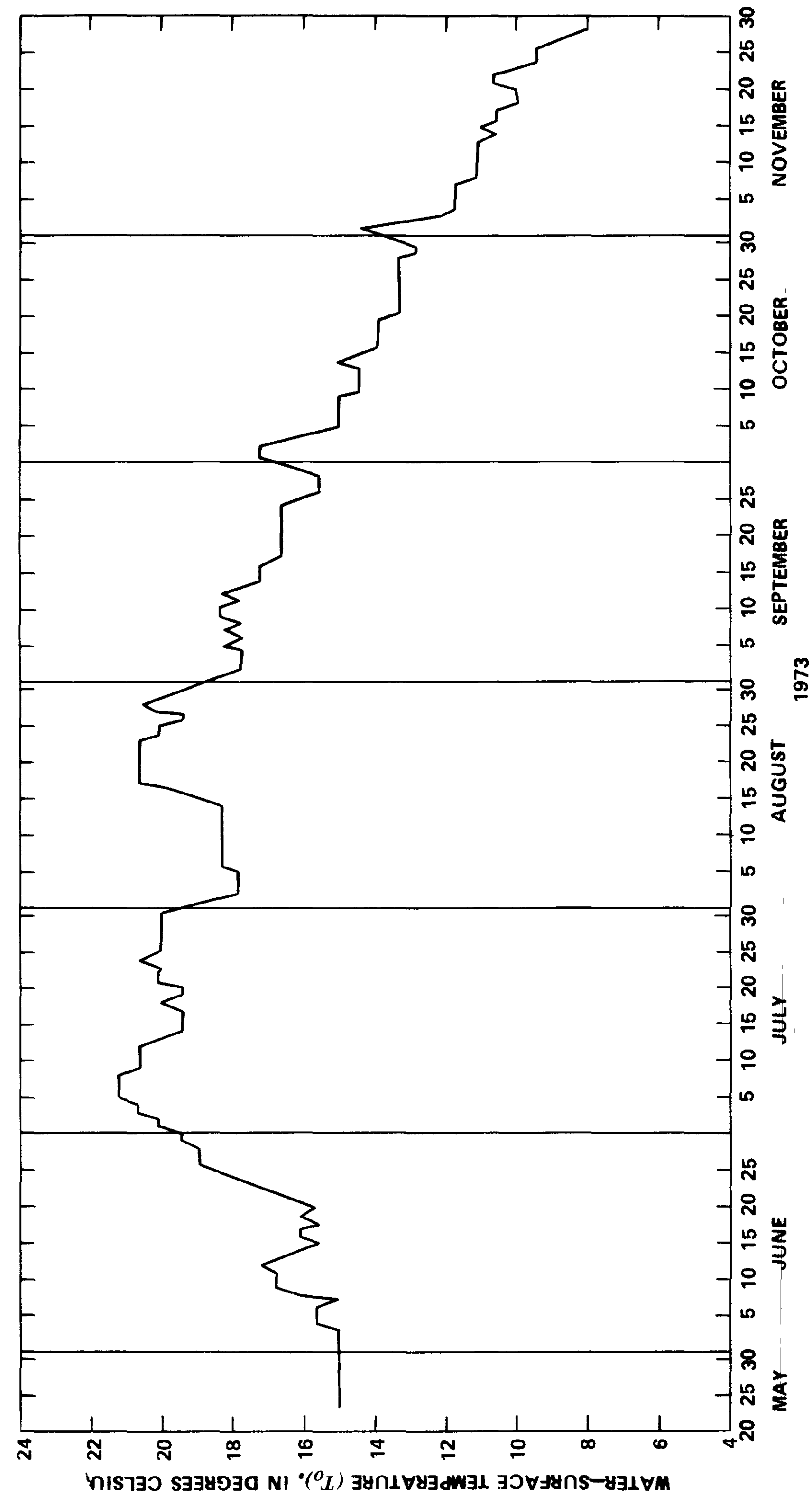

Figure 38.—Time graph of water-surface temperature, T_o, of Cheesman Reservoir.

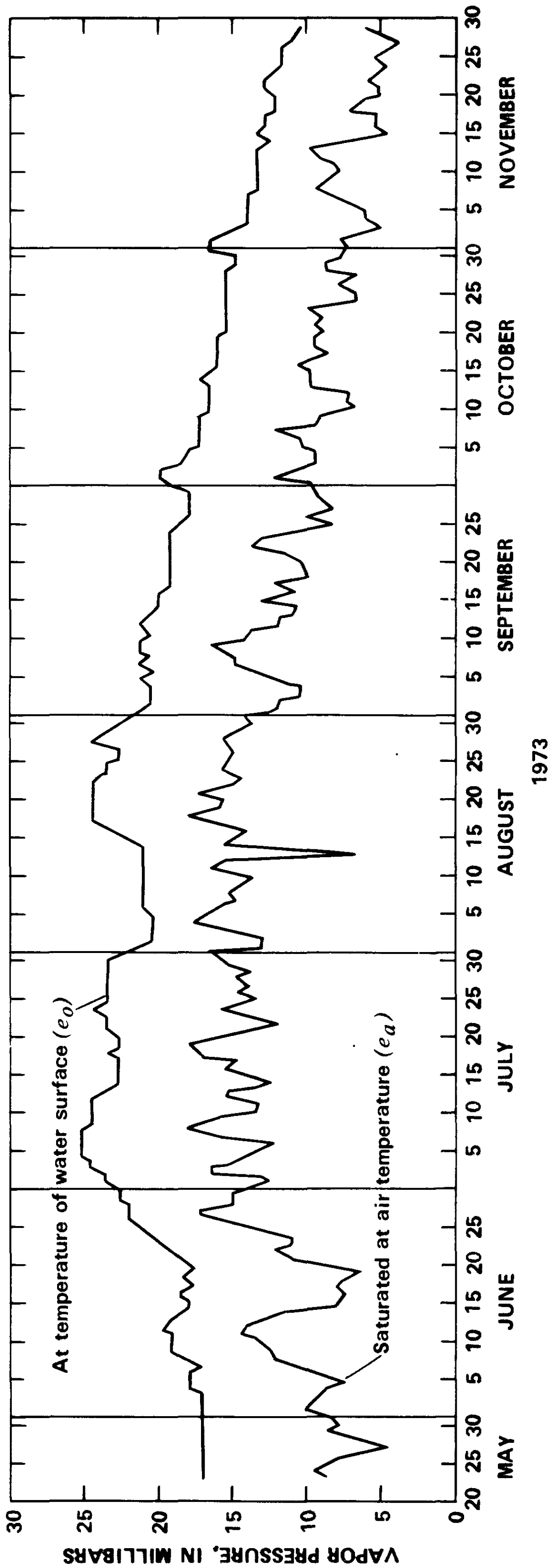

Figure 39.—Time graph of vapor pressures, e_o and e_a, at Cheesman Reservoir.

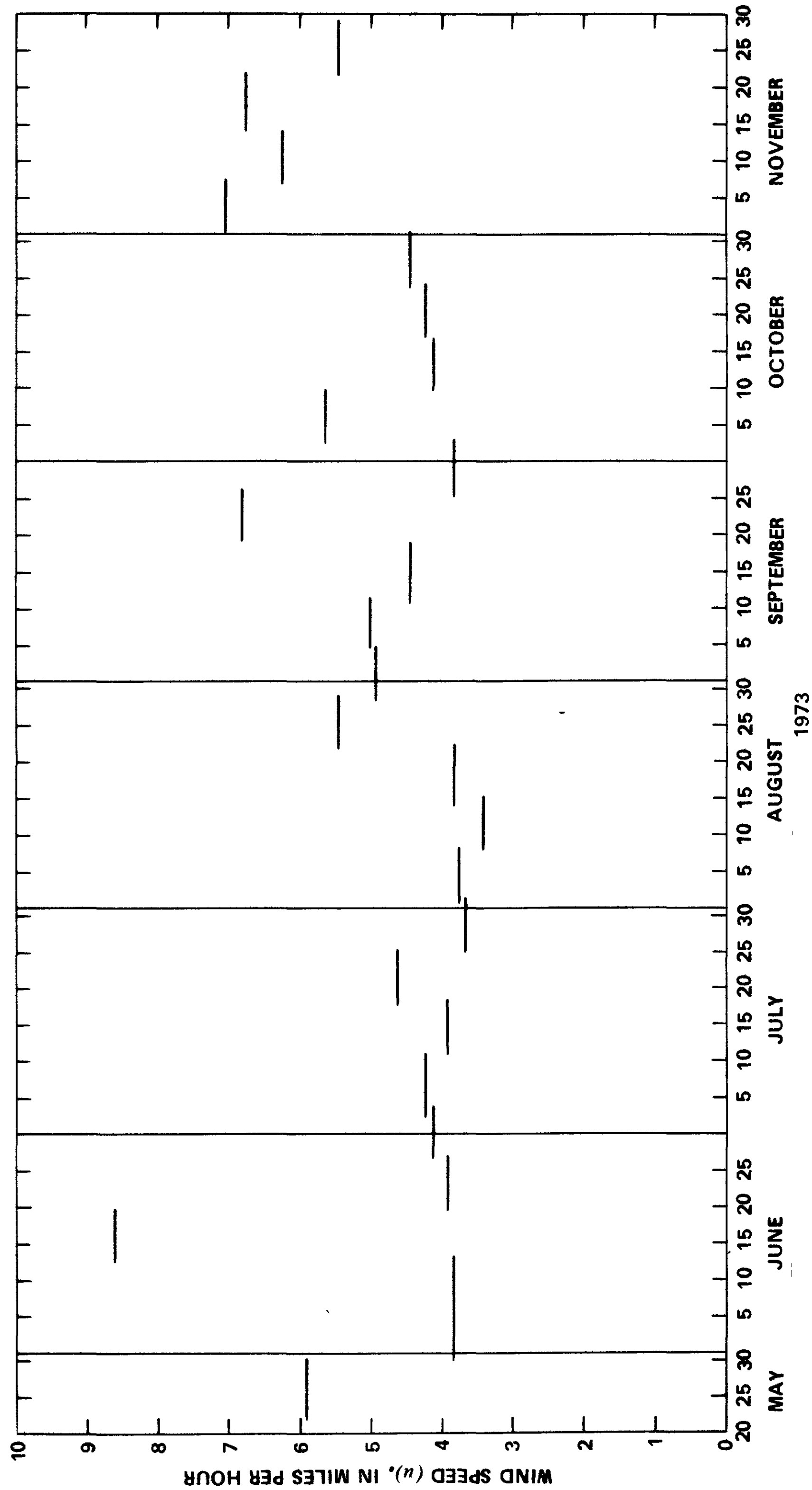

Figure 40.—Time graph of wind speeds, *u*, at Cheesman Reservoir.

EVAPORATION FROM WILLIAMS FORK RESERVOIR

The present dam for Williams Fork Reservoir was completed in 1959 for the purpose of generating power and providing storage to replace that water diverted from the Colorado River Basin into the Denver Board of Water Commissioners' system. Water released from the reservoir enters the Colorado River near Parshall, Colo. The reservoir is in a hill setting, with a north-south orientation, and the prevailing wind is from the west. The reservoir, supplied by the Williams Fork River, has a drainage area of 230 mi^2 (596 km^2). The storage capacity is 96,822 acre-ft (119 hm^3) with a surface area of 1,618 acres (6.55 km^2), mean depth of 59.8 ft (18.2 m), and maximum depth of 169 ft (55.5 m).

Evaporation studies of Williams Fork Reservoir were begun in 1969. Evaporation measurement by the mass-transfer method and by standard class-A pan were conducted for 5 years, 1969-73. The mass-transfer calculations from existing and future data can be improved by N-value calibration from future energy-budget studies.

Measurements of air temperature, relative humidity, and pan evaporation used in mass-transfer and pan studies were made at instruments located about 900 ft (295 m) from the dam. Temperatures of the reservoir surface and average wind speed were measured by instruments attached to a raft anchored near the center of the reservoir.

Mass-Transfer Records

The value of N for Williams Fork Reservoir as computed by Harbeck's equation (equation 8 of this report) was found to be 0.006.

Data.--Evaporation records for Williams Fork Reservoir as computed by the mass-transfer method for the 5 years of study, 1969-73, are summarized in table 14. Computation records for the 5 years generally are 1 week in length, representing the usual period between readings of the dials of the totalizing anemometer. Evaporation hydrographs for the 5 years of record are shown on figure 41.

Examples of water-surface temperature, T_o, saturation vapor pressure at temperature of water surface, e_o, with air vapor pressure, e_a, and wind speed, u_2, are shown on figures 42, 43, and 44, respectively.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir or pan exposure. The class-A pan evaporation from Williams Fork Reservoir is listed in table 14 with the mass-transfer evaporation.

Pan evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratios also are listed and, as can be seen, the ratios differ little from season to season, but are significantly different from the common 0.7 coefficient. The ratios for Williams Fork Reservoir were uniform and have been calibrated against mass-transfer evaporation data employing Harbeck's N values. In the event that it is determined that the pan method needs to be used to determine evaporation at this facility, the pan ratio needs to be calibrated against a more reliable method of evaporation determination, such as the energy-budget method.

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	5	May 23- May 28	5.6	7.6	0.26	1.28	37.50	----	----
2	7	May 28- June 4	7.7	8.5	.39	2.75	86.88	----	----
3	7	June 4- June 11	6.9	8.0	.33	2.32	79.62	3.78	0.61
4	7	June 11- June 18	5.2	6.6	.21	1.44	53.10	1.60	.90
5	8	June 18- June 26	7.9	7.1	.34	2.69	109.79	3.33	.81
6	6	June 26- July 2	8.7	6.9	.36	2.16	94.25	3.45	.63
7	7	July 2- July 9	7.7	7.0	.32	2.26	102.17	5.08	.44
8	7	July 9- July 16	5.4	9.9	.32	2.25	104.60	5.18	.43
9	7	July 16- July 23	5.7	10.3	.35	2.47	117.02	4.04	.61
10	7	July 23- July 30	6.1	11.6	.42	2.97	142.85	5.13	.58
11	7	July 30- Aug. 6	5.8	11.0	.38	2.68	130.66	4.72	.57
12	7	Aug. 6- Aug. 13	6.5	12.2	.48	3.33	161.69	5.79	.58

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1969			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
13	7	Aug. 13- Aug. 20	5.6	11.5	0.39	2.70	129.68	3.96	0.68
14	7	Aug. 20- Aug. 27	5.4	11.0	.36	2.49	118.29	3.61	.69
15	7	Aug. 27-Sept. 3	6.0	10.8	.39	2.72	126.99	4.06	.67
16	7	Sept. 3-Sept. 10	6.9	10.3	.43	2.98	136.88	3.68	.81
17	7	Sept. 10-Sept. 17	5.9	9.4	.33	2.33	105.57	2.36	.99
18	7	Sept. 17-Sept. 24	5.9	9.1	.32	2.25	101.13	1.83	1.23
19	7	Sept. 24- Oct. 1	5.8	9.2	.32	2.24	99.73	3.00	.75
20	7	Oct. 1- Oct. 8	6.9	9.2	.38	2.67	118.08	----	----
21	7	Oct. 8- Oct. 15	9.0	9.0	.49	3.40	149.36	----	----
22	7	Oct. 15- Oct. 22	5.9	7.2	.25	1.78	77.55	----	----
23	5	Oct. 22- Oct. 27	5.1	----	----	----	-----	----	----
Record season	152	May 23- Oct. 22			0.36	54.16	2,383.39		
Pan season	119	June 4- Oct. 1			0.36	42.28		64.60	0.65

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
24	9	June 1- June 9	6.6	6.7	0.265	2.39	90.25	5.00	0.48
25	6	June 9- June 15	7.9	5.8	.275	1.65	66.86	2.18	.76
26	8	June 15- June 23	6.3	6.1	.231	1.84	79.08	5.56	.33
27	6	June 23- June 29	7.1	6.6	.281	1.69	77.85	4.42	.38
28	7	June 29- July 6	5.9	8.8	.312	2.18	104.56	5.94	.37
29	7	July 6- July 13	5.8	9.2	.320	2.24	108.77	3.73	.60
30	7	July 13- July 20	6.0	9.9	.356	2.50	121.39	4.75	.53
31	7	July 20- July 27	6.4	9.7	.372	2.61	125.53	4.32	.60
32	7	July 27- Aug. 3	6.3	9.9	.374	2.62	124.64	5.08	.52
33	7	Aug. 3- Aug. 10	5.7	9.6	.328	2.30	108.81	4.32	.53

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1970			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
34	7	Aug. 10- Aug. 17	5.7	11.4	0.390	2.73	127.99	4.27	0.64
35	8	Aug. 17- Aug. 25	5.1	9.8	.300	2.40	110.87	4.04	.59
36	6	Aug. 25- Aug. 31	6.1	8.4	.307	1.84	83.79	3.73	.49
37	7	Aug. 31-Sept. 7	8.0	10.1	.485	3.39	152.48	2.57	1.32
38	7	Sept. 7-Sept. 14	9.2	8.8	.486	3.40	151.26	3.56	.96
39	7	Sept. 14-Sept. 21	7.9	10.0	.474	3.32	146.61	3.76	.88
40	7	Sept. 21-Sept. 28	5.9	10.4	.368	2.58	113.34	----	----
41	7	Sept. 28- Oct. 5	4.7	8.6	.243	1.70	74.18	----	----
42	7	Oct. 5- Oct. 12	6.2	8.5	.316	2.21	95.93	----	----
43	7	Oct. 12- Oct. 19	4.6	8.0	.221	1.55	66.77	----	----
Record season	141	June 1- Oct. 19			0.334	47.14	2,130.96		
Pan season	113	June 1-Sept. 21			0.346	39.10		67.08	0.58

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
44	6.9	June 8- June 15	6.08	6.4	0.234	1.62	62.87	3.28	0.49
45	6.9	June 15- June 22	5.85	7.7	.269	1.87	80.57	5.05	.37
46	7.0	June 22- June 29	7.32	9.1	.396	2.79	135.2	7.34	.38
47	7.0	June 29- July 6	7.15	8.9	.378	2.65	139.1	5.66	.47
48	6.9	July 6- July 13	7.32	7.9	.343	2.38	126.0	5.66	.42
49	7.1	July 13- July 20	5.41	9.6	.310	2.19	115.9	5.51	.40
50	7.0	July 20- July 27	6.28	10.6	.397	2.77	147.4	4.72	.59
51	7.0	July 27- Aug. 3	7.01	12.3	.514	3.59	190.2	5.72	.63

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1971			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
52	7.0	Aug. 3- Aug. 10	6.10	10.2	0.370	2.58	135.4	5.38	0.48
53	7.0	Aug. 10- Aug. 17	6.01	9.0	.322	2.26	116.3	5.77	.39
54	7.0	Aug. 17- Aug. 24	6.06	9.2	.331	2.31	116.4	4.93	.47
55	7.0	Aug. 24- Aug. 31	5.55	8.2	.271	1.91	94.03	3.96	.48
56	7.0	Aug. 31-Sept. 7	7.54	10.6	.476	3.34	161.9	3.43	.97
57	6.9	Sept. 7-Sept. 14	5.98	10.5	.376	2.61	124.4	4.22	.62
58	7.1	Sept. 14-Sept. 21	9.02	11.7	.630	4.46	207.9	2.44	1.83
59	14.0	Sept. 21- Oct. 5	7.90	9.2	.436	6.09	275.8	5.51	1.11
Record season	118.8	June 8- Oct. 5			0.382	45.42	2,229.37		
Pan season	118.8	June 8- Oct. 5			0.382	45.42		78.58	0.58

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
60	7.0	May 30- June 6	5.33	5.2	0.167	1.18	42.87	3.00	0.39
61	7.0	June 6- June 12	5.93	8.2	.293	2.05	83.02	4.06	.50
62	6.9	June 13- June 20	7.31	8.3	.362	2.51	109.70	3.84	.65
63	7.0	June 20- June 27	8.27	8.3	.412	2.89	132.90	4.60	.63
64	7.0	June 27- July 4	6.89	9.5	.389	2.72	128.80	5.26	.52
65	7.0	July 4- July 11	5.92	8.5	.299	2.10	100.90	3.94	.53
66	7.0	July 11- July 18	6.86	7.8	.321	2.24	108.90	5.23	.43
67	7.0	July 18- July 25	7.26	7.7	.332	2.32	113.00	5.54	.42
68	7.0	July 25- Aug. 1	5.52	8.1	.268	1.87	91.68	4.24	.44
69	7.0	Aug. 1- Aug. 8	6.01	8.9	.321	2.25	109.70	3.63	.62

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
70	7.0	Aug. 8- Aug. 15	6.42	9.5	0.364	2.54	122.90	6.02	0.42
71	7.0	Aug. 15- Aug. 22	5.65	8.7	.294	2.07	99.04	2.49	.83
72	6.9	Aug. 22- Aug. 29	6.08	7.1	.257	1.78	84.03	3.25	.55
73	7.0	Aug. 29-Sept. 5	5.14	6.6	.203	1.42	66.55	1.65	.86
74	7.0	Sept. 5-Sept. 12	6.42	6.3	.242	1.70	78.88	1.83	.93
75	6.9	Sept. 12-Sept. 19	6.95	8.5	.351	2.44	112.80	3.20	.76
76	7.0	Sept. 19-Sept. 26	8.13	8.1	.392	2.75	126.70	2.59	1.06
77	7.0	Sept. 26- Oct. 3	8.37	7.5	.374	2.62	120.20	----	----
78	9.1	Oct. 3- Oct. 12	5.68	4.0	.134	1.23	56.20	----	----
79	4.9	Oct. 12- Oct. 17	6.33	4.3	.163	.80	36.45	----	----
80	7.0	Oct. 17- Oct. 24	5.38	4.7	.152	1.06	48.66	----	----
Record season	146.7	May 30- Oct. 24			0.290	42.55	1,973.88		
Pan season	118.7	May 30-Sept. 26			0.310	36.84		64.37	0.57

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
81	7.0	June 5- June 12	5.5	5.9	0.197	1.37	53.63	----	----
82	7.9	June 12- June 20	9.2	7.2	.399	3.16	135.40	----	----
83	6.0	June 20- June 26	5.92	5.8	.204	1.24	55.41	----	----
84	6.0	June 26- July 2	6.47	7.8	.302	1.81	86.49	----	----
85	8.1	July 2- July 10	6.24	7.1	.265	2.16	107.50	7.06	0.31
86	6.8	July 10- July 17	6.09	8.2	.297	2.01	102.20	3.38	.59
87	7.1	July 17- July 24	5.82	7.4	.256	1.81	93.29	3.05	.59
88	6.9	July 24- July 31	5.44	7.4	.240	1.66	86.01	3.96	.42
89	7.0	July 31- Aug. 7	5.42	7.2	.232	1.62	83.61	3.00	.54
90	9.3	Aug. 7- Aug. 16	5.51	7.6	.248	2.31	117.50	5.28	.44
91	6.7	Aug. 16- Aug. 23	5.54	5.8	.193	1.29	64.82	4.17	.31

Table 14.--*Summary of mass-transfer terms and pan evaporation for Williams Fork Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
92	5.1	Aug. 23- Aug. 28	7.29	6.9	0.300	1.52	75.38	2.62	0.58
93	7.9	Aug. 28-Sept. 5	6.34	9.4	.356	2.83	137.40	4.06	.70
94	8.0	Sept. 5-Sept. 13	6.03	8.1	.290	2.32	110.20	3.25	.71
95	6.0	Sept. 13-Sept. 19	7.04	9.2	.389	2.33	107.80	2.46	.95
96	7.0	Sept. 19-Sept. 26	8.36	8.2	.413	2.89	130.90	2.79	1.04
97	7.0	Sept. 26- Oct. 3	6.14	7.7	.282	1.97	87.42	----	----
98	7.0	Oct. 3- Oct. 10	7.25	7.2	.314	2.19	94.71	----	----
99	7.0	Oct. 10- Oct. 17	6.67	7.6	.304	2.14	90.52	----	----
100	7.0	Oct. 17-Oct. 24	6.31	7.2	.273	1.90	78.25	----	----
101	7.0	Oct. 24- Oct. 31	7.05	7.4	.313	2.21	88.28	----	----
102	7.0	Oct. 31- Nov. 7	8.3	7.4	.370	2.59	101.30	----	----
Record season	154.8	June 5- Nov. 7			0.293	45.33	2,088.02		
Pan season	85.9	July 2-Sept. 26			0.288	24.75		45.08	0.55

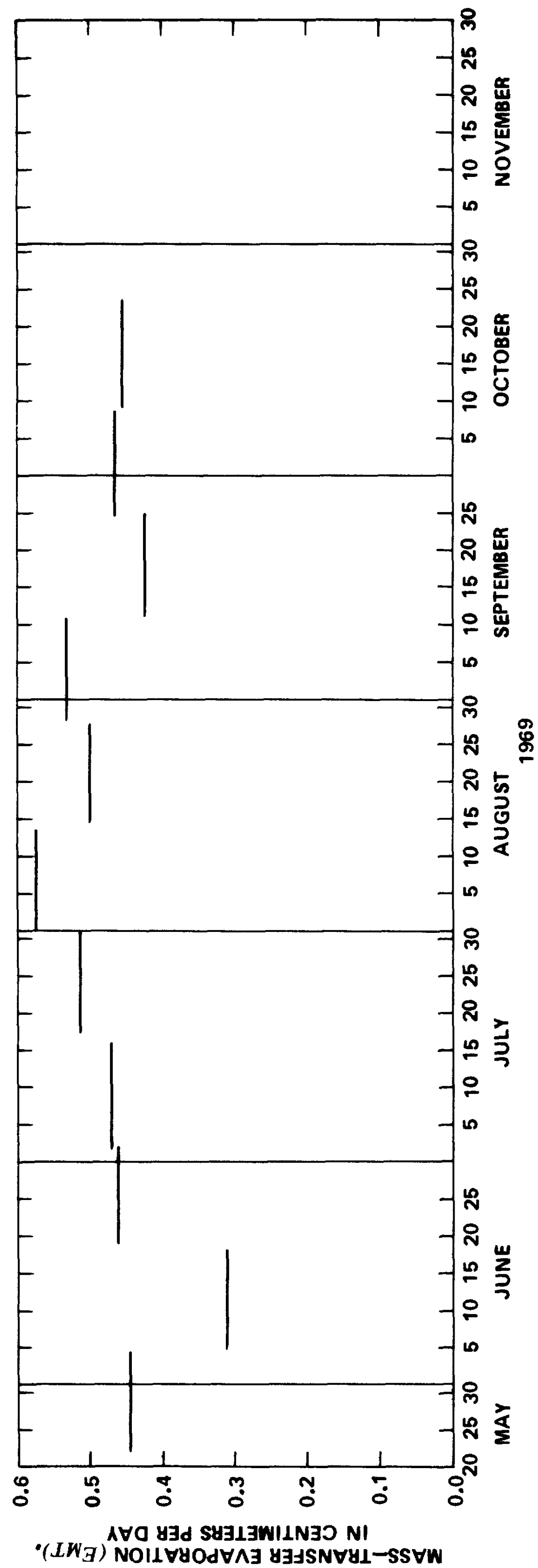

Figure 41.—Rates of mass–transfer evaporation, E_{MT}, from Williams Fork Reservoir for the 1969–73 record seasons.

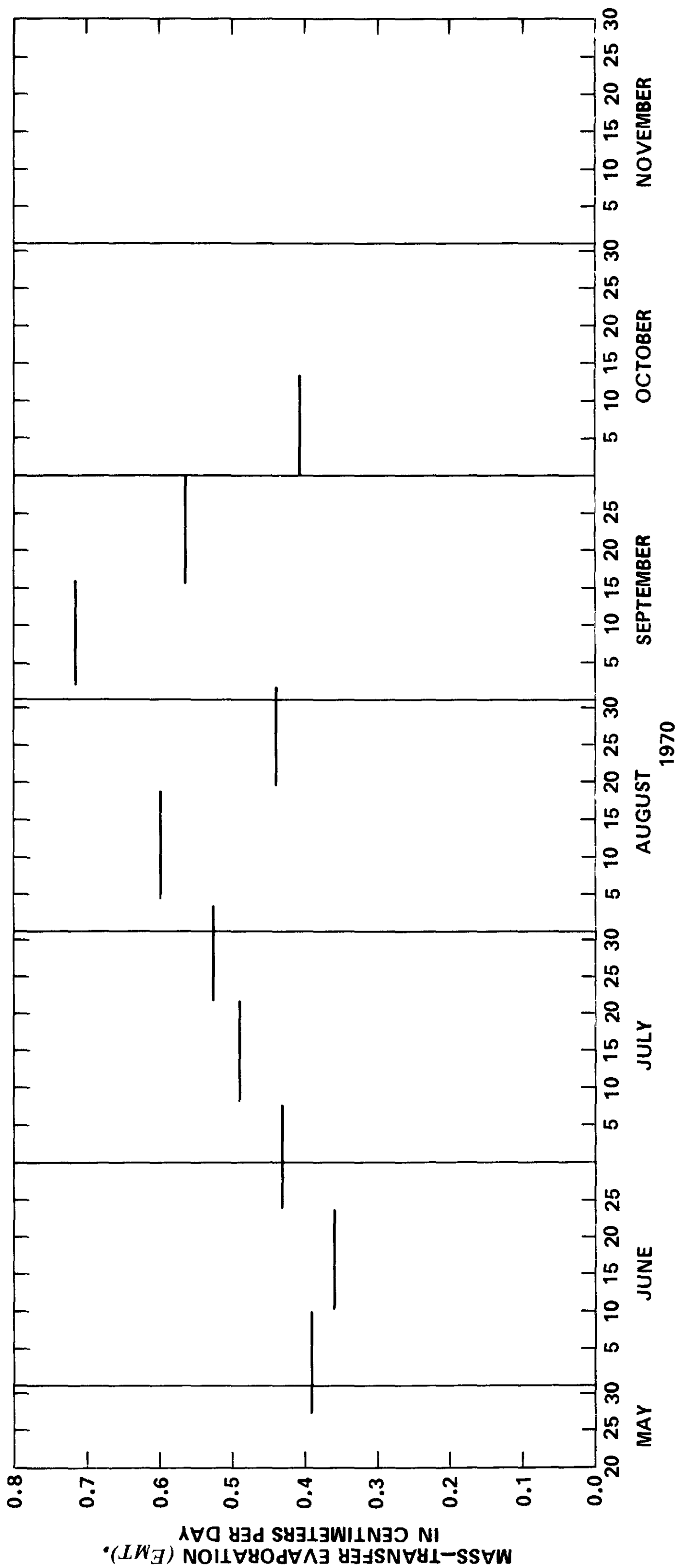

Figure 41.--Rates of mass-transfer evaporation, E_{MT}, from Williams Fork Reservoir for the 1969–73 record seasons--Continued.

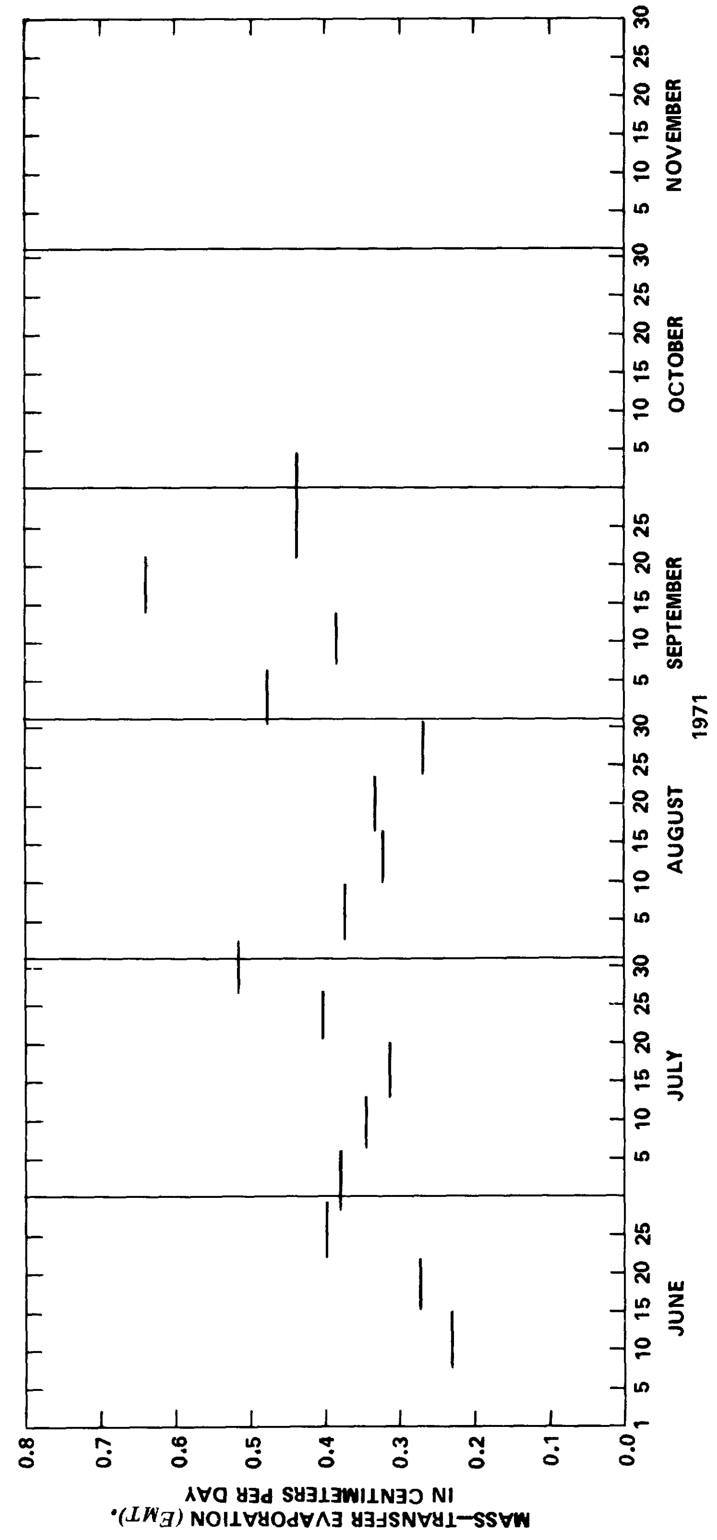

Figure 41.—Rates of mass-transfer evaporation, E_{MT}, from Williams Fork Reservoir for the 1969–73 record seasons—Continued.

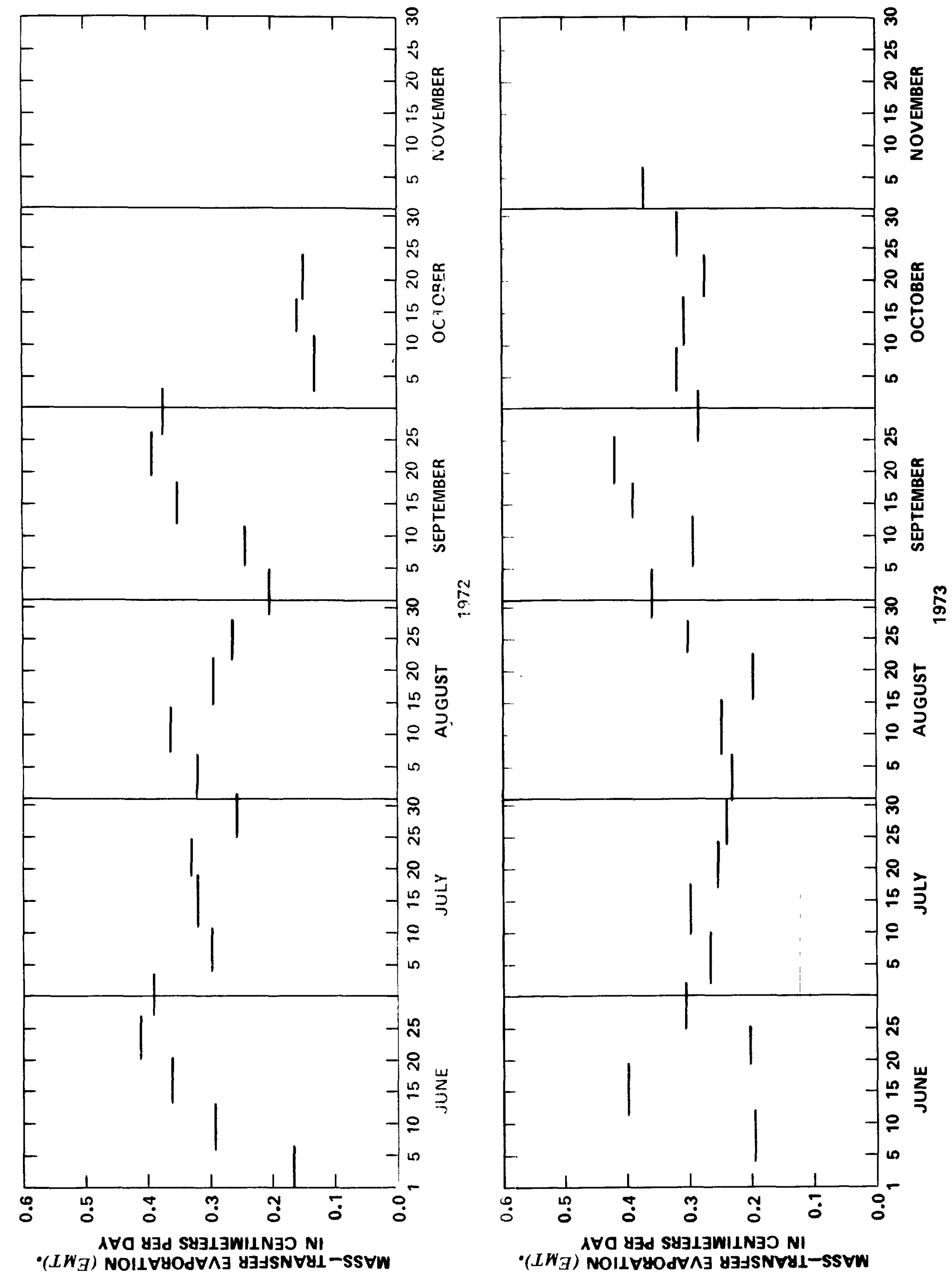

Figure 41.—Rates of mass-transfer evaporation, E_{MT}, from Williams Fork Reservoir for the 1969–73 record seasons—Continued.

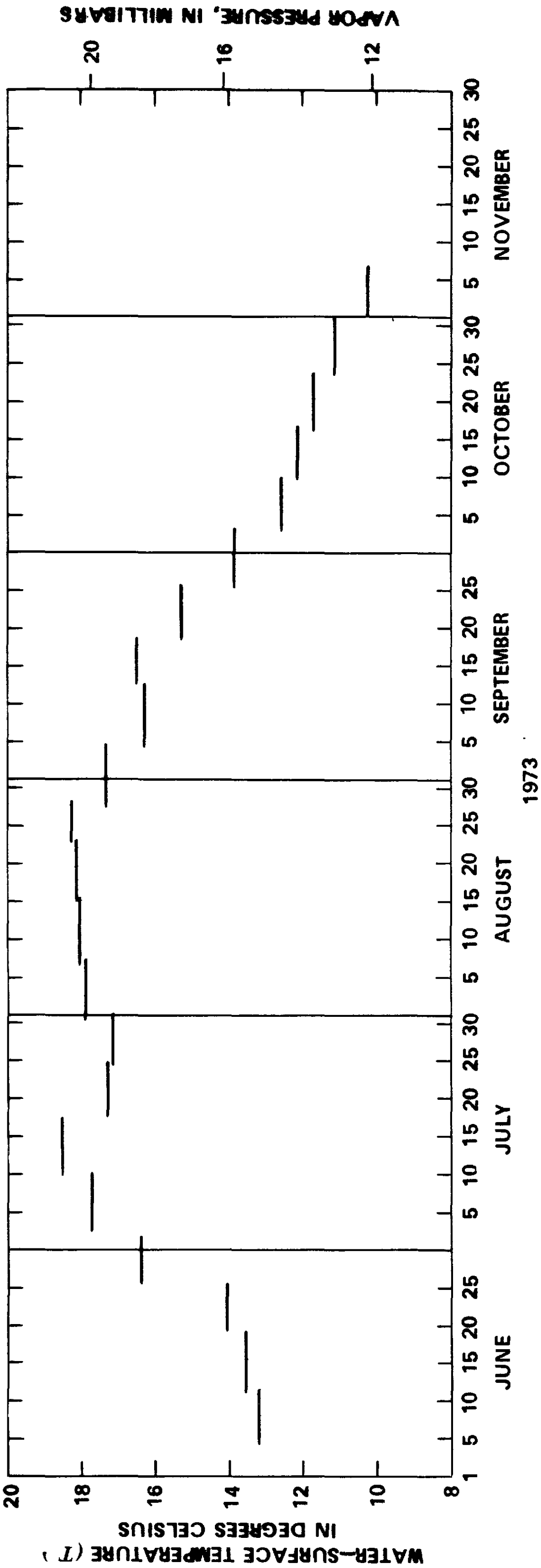

Figure 42.—Time graph of water-surface temperature, T_o, of Williams Fork Reservoir.

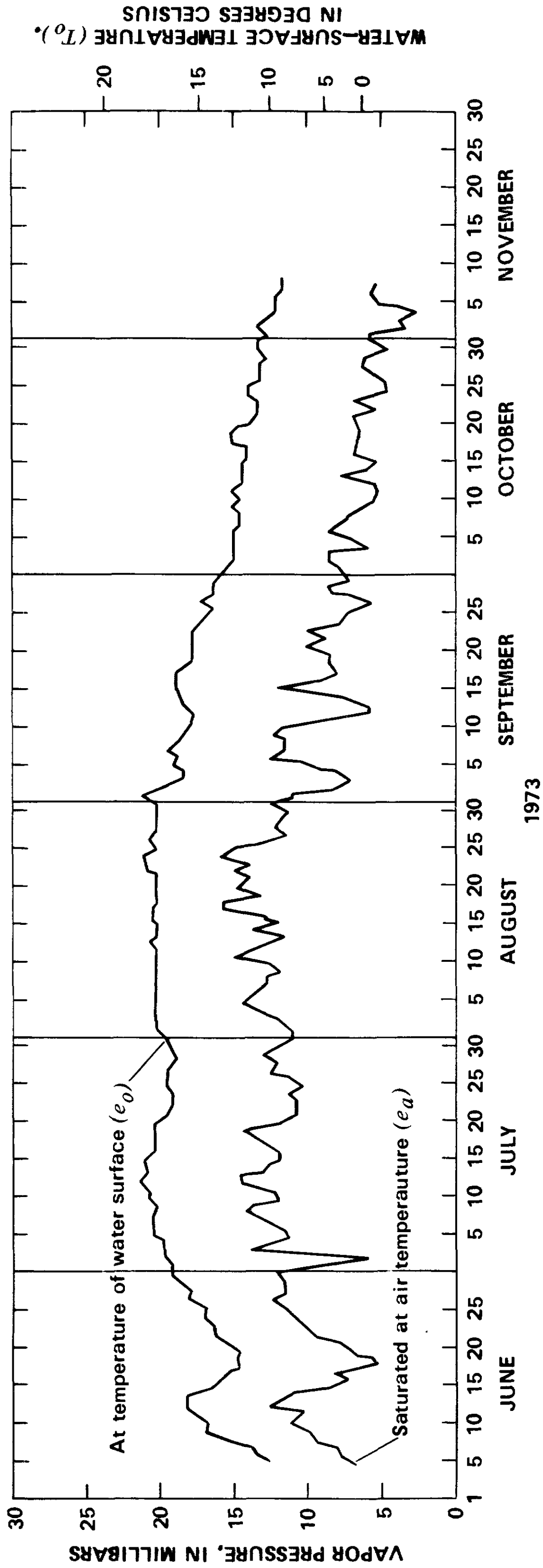

Figure 43.—Time graph of vapor pressures, e_o and e_a, at Williams Fork Reservoir.

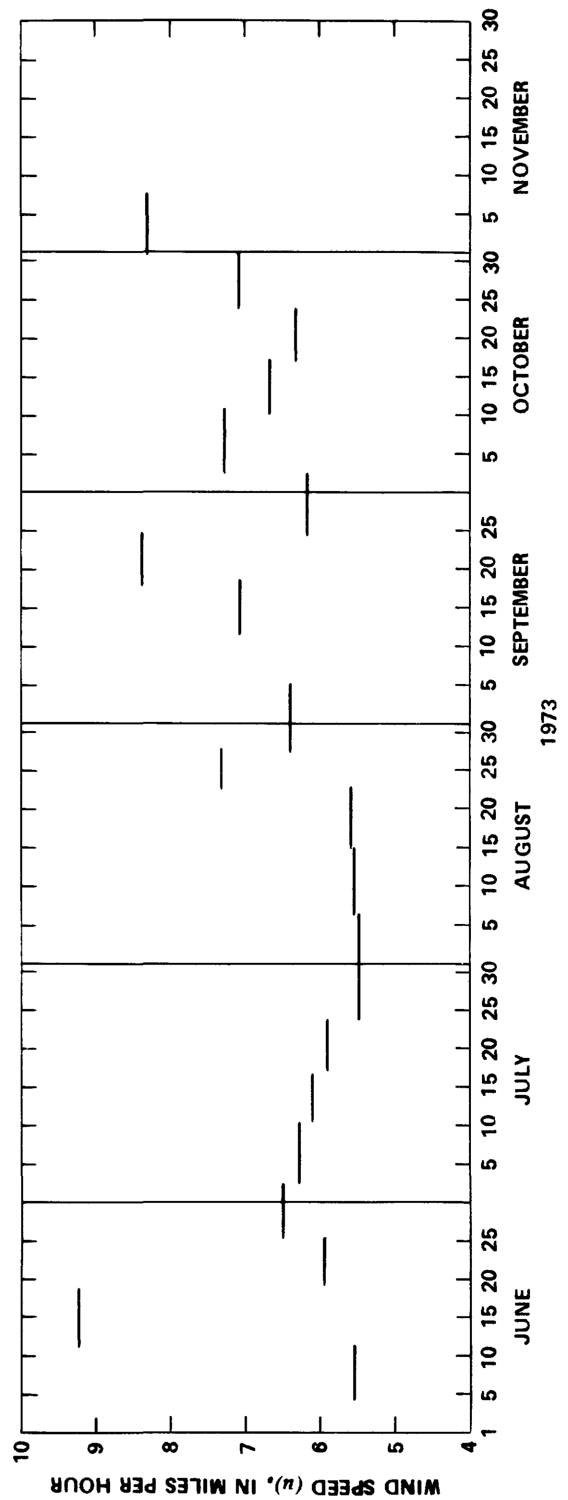

Figure 44.—Time graph of wind speeds, *u*, at Williams Fork Reservoir.

EVAPORATION FROM RALSTON RESERVOIR

The Ralston dam was completed in 1937. The reservoir presently provides intermediate storage of water delivered from Gross Reservoir via South Boulder Creek. The reservoir supplies water to the Moffat treatment plant and various other customers north and east of Golden, Colo. The reservoir is located on Ralston Creek in a small canyon in the foothills where the Colorado Plains meet the Rocky Mountains. The reservoir is oriented in a northeast-southwest direction with the prevailing wind from the west. The main source of water is the South Boulder Canal heading at the Eldorado Springs Diversion on South Boulder Creek, but Ralston Creek also supplies a minimal amount. Ralston Reservoir has a drainage area of 46 mi^2 (119 km^2). The storage capacity is 11,218 acre-ft (13.8 hm^3), with a surface area of 225 acres (0.91 km^2), mean depth of 49.9 ft (15.2 m), and maximum depth of 151 ft (46 m).

Evaporation studies of Ralston Reservoir were begun in 1972. Evaporation measurements by the mass-transfer method and by standard class-A pan were conducted for 2 years, 1972-73. The mass-transfer calculations from existing and future data can be improved by N-value calibration from future energy-budget studies. Measurements of air temperature, relative humidity used in mass-transfer, and pan studies were made at instruments located at the caretaker's house about 500 ft (150 m) downstream from the dam. Pan evaporation was measured atop the dam. Temperatures of the reservoir surface and average wind speed were measured by instruments attached to a raft anchored near the center of the reservoir.

Mass-Transfer Records

The value of N for Ralston Reservoir as computed by Harbeck's equation (equation 8 of this report) was found to be 0.00667.

Data.--Evaporation records for Ralston Reservoir as computed by the mass-transfer method for the 2 years of study, 1972-73, are summarized in table 15. Computation periods for the 2 years generally are 1 week in length, representing the usual period between readings of the dials of the totalizing anemometer. Evaporation hydrographs for the 2 years of record are shown on figure 45.

Examples of water-surface temperature, T_o, saturation vapor pressure at temperature of water surface, e_o, with air vapor pressure, e_a, and wind speed, u_2, are shown on figures 46, 47, and 48, respectively.

Pan-Evaporation Records

Pan evaporation has long been thought to be a simple method of estimating annual reservoir and pond evaporation by simply multiplying pan evaporation by a coefficient, commonly 0.7, that has no relation to the reservoir

Table 15.--*Summary of mass-transfer terms and pan evaporation for Ralston Reservoir*

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1972			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
1	16.2	June 26- July 12	5.65	5.8	0.220	3.57	19.50	----	----
2	27.9	July 12- Aug. 9	5.52	5.2	.193	5.36	28.75	----	----
3	7.0	Aug. 9- Aug. 16	5.94	6.4	.253	1.77	8.94	7.77	0.23
4	7.0	Aug. 16- Aug. 23	6.15	2.9	.117	.822	4.48	6.32	.13
5	7.0	Aug. 23- Aug. 30	5.38	2.3	.083	.580	3.20	3.63	.16
6	7.0	Aug. 30-Sept. 6	6.01	3.1	.122	.856	4.63	6.15	.14
7	7.0	Sept. 6-Sept. 13	5.17	2.0	.070	.488	2.62	2.72	.18
8	7.0	Sept. 13-Sept. 20	7.31	6.1	.298	2.09	11.33	6.15	.34
9	7.0	Sept. 20-Sept. 27	5.34	8.0	.285	2.00	10.63	4.88	.41
10	7.0	Sept. 27- Oct. 4	5.83	8.4	.325	2.27	11.95	5.56	.41
11	7.0	Oct. 4- Oct. 11	4.21	6.3	.177	1.24	6.71	2.57	.48
12	7.0	Oct. 11- Oct. 18	5.39	6.6	.235	1.64	9.04	4.06	.40
13	7.0	Oct. 18- Oct. 25	4.51	6.0	.179	1.25	6.78	1.47	.85
Record season	121.1	June 26- Oct. 25			0.198	23.94			
Pan season	77.0	Aug. 9- Oct. 25			0.194	15.01		51.28	0.29

Table 15.--*Summary of mass-transfer terms and pan evaporation for Ralston Reservoir*--Continued

No.	Period: Length (days)	Period: Dates 1973	$u_{2.0}$ (miles per hour)	$e_o - e_a$ (millibars)	Reservoir evaporation computed by mass-transfer method: Centimeters per day	Centimeters per period	Acre-feet per period	Pan evaporation: Centimeters per period	Ratio of reservoir to pan evaporation
14	7.0	May 30- June 6	5.92	9.2	0.362	2.53	12.93	3.07	0.82
15	7.0	June 6- June 13	8.84	9.4	.557	3.90	19.78	7.49	.52
16	7.0	June 13- June 20	6.06	10.6	.430	3.02	15.77	7.29	.41
17	7.0	June 20- June 27	5.43	10.1	.364	2.56	13.27	8.00	.32
18	7.0	June 27- July 4	6.62	8.5	.373	2.62	13.66	7.44	.35
19	6.9	July 4- July 11	6.5	8.3	.359	2.49	13.42	8.43	.30
20	7.0	July 11- July 18	4.98	7.1	.235	1.65	8.96	5.79	.28
21	7.1	July 18- July 25	5.44	8.3	.301	2.12	11.43	3.02	.70
22	7.0	July 25- Aug. 1	7.39	11.3	.553	3.85	20.93	4.17	.92
23	7.0	Aug. 1- Aug. 8	6.24	11.4	.475	3.30	17.70	6.83	.48
24	7.0	Aug. 8- Aug. 15	5.76	12.6	.484	3.39	17.99	7.37	.46
25	7.1	Aug. 15- Aug. 22	6.25	10.2	.426	3.01	15.96	7.54	.40
26	7.0	Aug. 22- Aug. 29	6.48	9.1	.393	2.75	14.62	7.85	.35

Table 15.--*Summary of mass-transfer terms and pan evaporation for Ralston Reservoir*--Continued

Period			$u_{2.0}$ (miles per hour)	e_o-e_a (millibars)	Reservoir evaporation computed by mass-transfer method			Pan evaporation	Ratio of reservoir to pan evaporation
No.	Length (days)	Dates 1973			Centimeters per day	Centimeters per period	Acre-feet per period	Centimeters per period	
27	7.0	Aug. 29-Sept. 5	4.89	9.7	0.316	2.22	11.72	5.94	0.37
28	6.9	Sept. 5-Sept. 12	4.73	8.0	.252	1.75	9.46	6.68	.26
29	7.0	Sept. 12-Sept. 19	6.07	9.7	.393	2.74	14.52	3.07	.89
30	7.0	Sept. 19-Sept. 26	5.76	9.5	.367	2.57	12.19	5.46	.47
31	6.9	Sept. 26- Oct. 3	5.70	8.9	.339	2.33	10.15	2.64	.88
32	7.0	Oct. 3- Oct. 10	5.59	9.4	.355	2.47	10.51	3.99	.62
33	7.0	Oct. 10- Oct. 17	7.40	9.5	.475	3.33	13.96	2.41	1.38
34	8.0	Oct. 17- Oct. 25	4.38	10.5	.311	2.50	10.31	5.82	.43
35	6.0	Oct. 25- Oct. 31	6.61	8.4	.375	2.23	9.06	3.45	.65
36	7.2	Oct. 31- Nov. 7	5.62	7.5	.284	2.03	8.15	1.57	1.29
37	6.9	Nov. 7- Nov. 14	6.20	7.3	.306	2.12	8.50	3.48	.61
38	7.0	Nov. 14- Nov. 21	8.33	5.9	.327	2.30	11.43	3.81	.60
39	8.0	Nov. 21- Nov. 29	5.48	5.1	.187	1.49	7.89	----	----
Record season	183.0	May 30- Nov. 29			0.359	65.78			
Pan season	175.0	May 30- Nov. 21			0.367	64.29		132.61	0.48

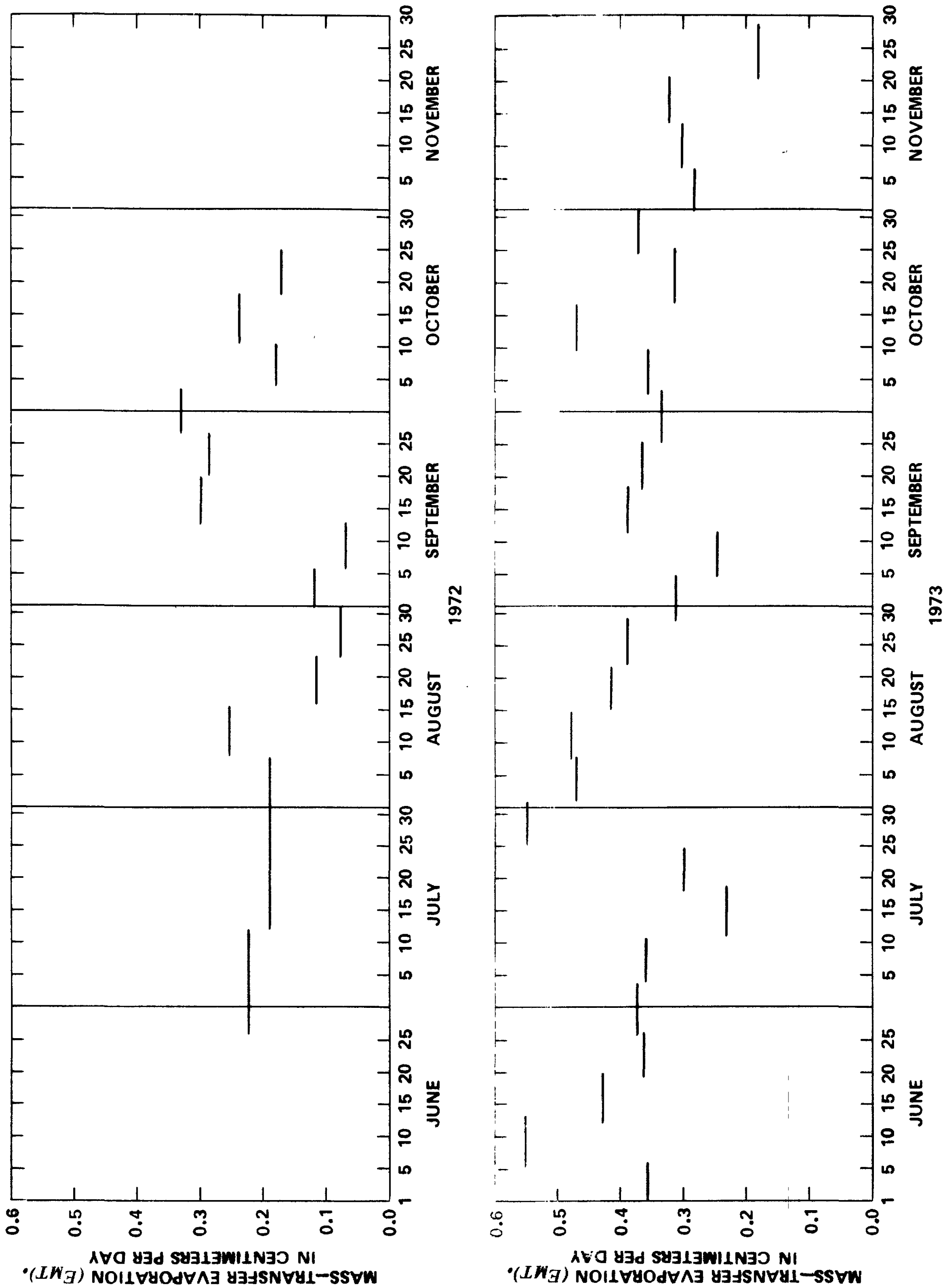

Figure 45.—Rates of mass-transfer evaporation, E_{MT}, from Ralston Reservoir for the 1972–73 record seasons.

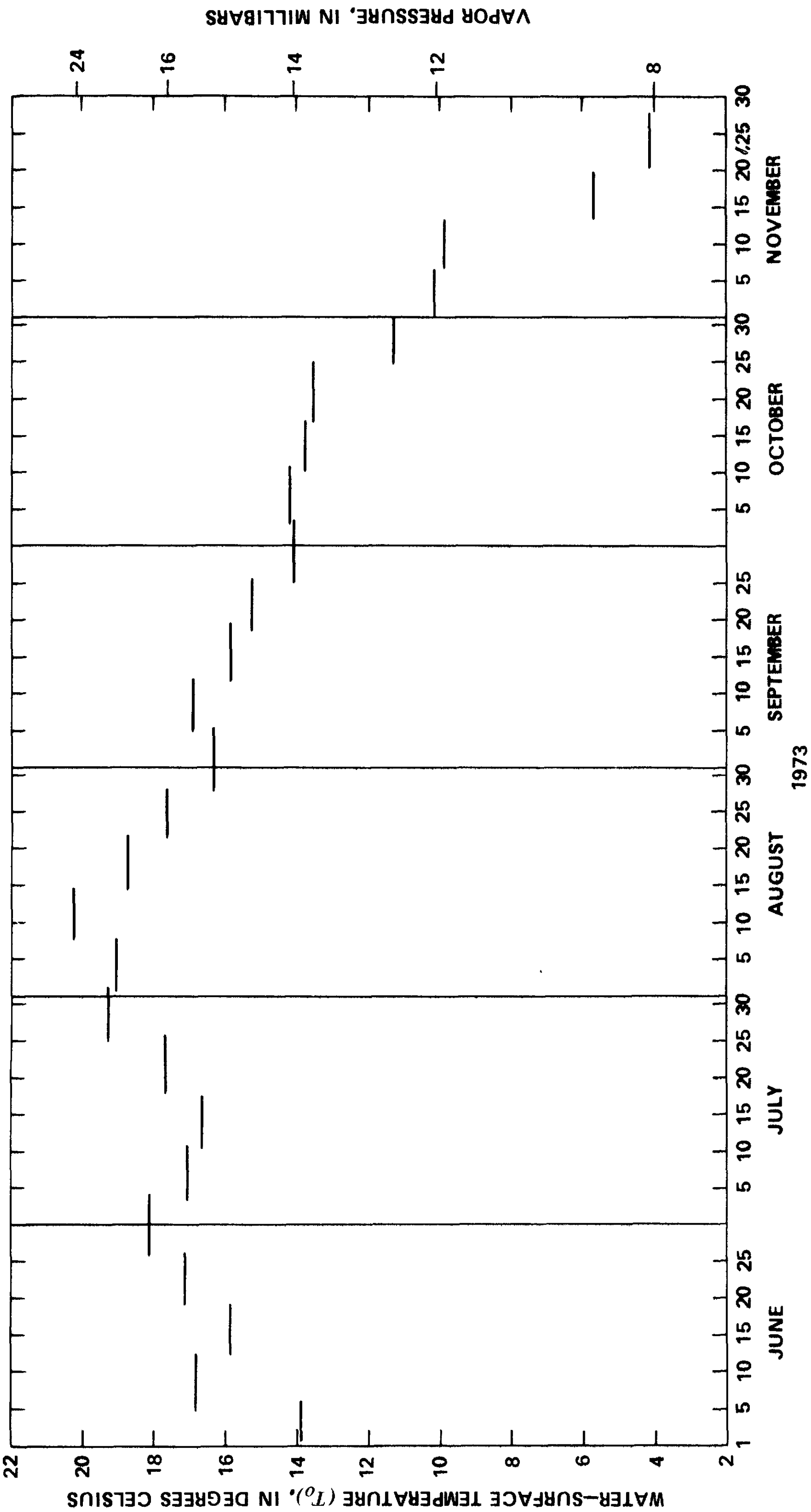

Figure 46.—Time graph of water–surface temperature, T_o, of Ralston Reservoir.

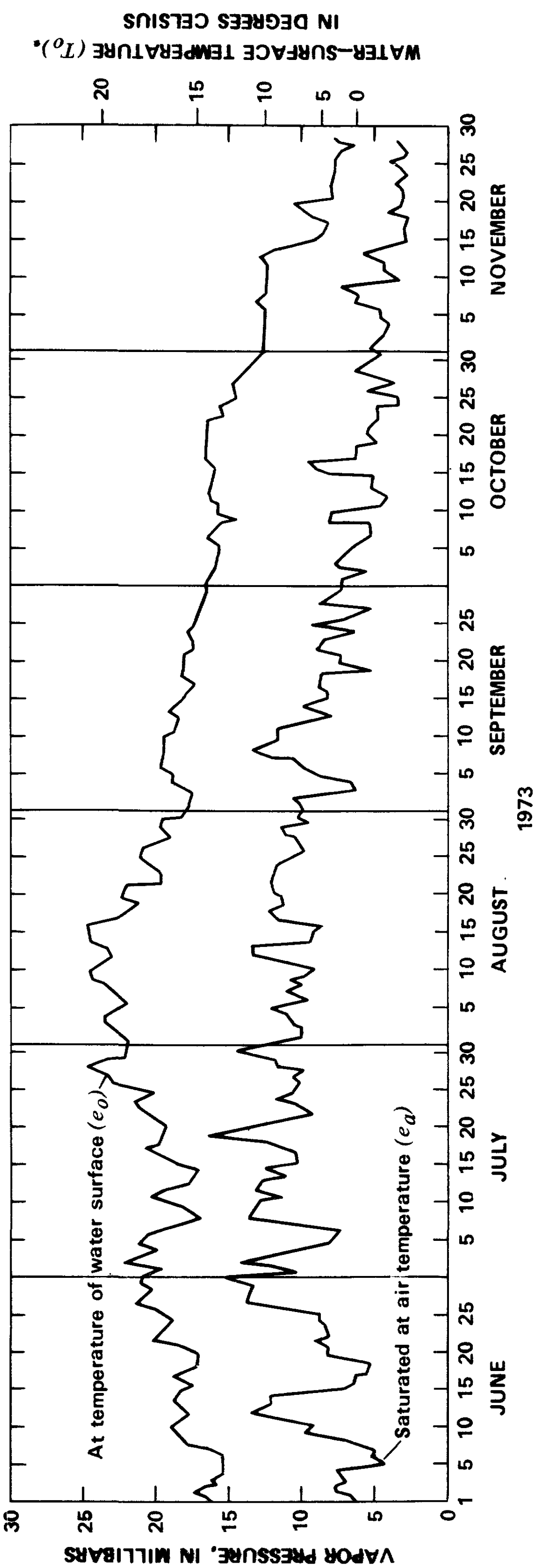

Figure 47.—Time graph of vapor pressures, e_o and e_a, at Ralston Reservoir.

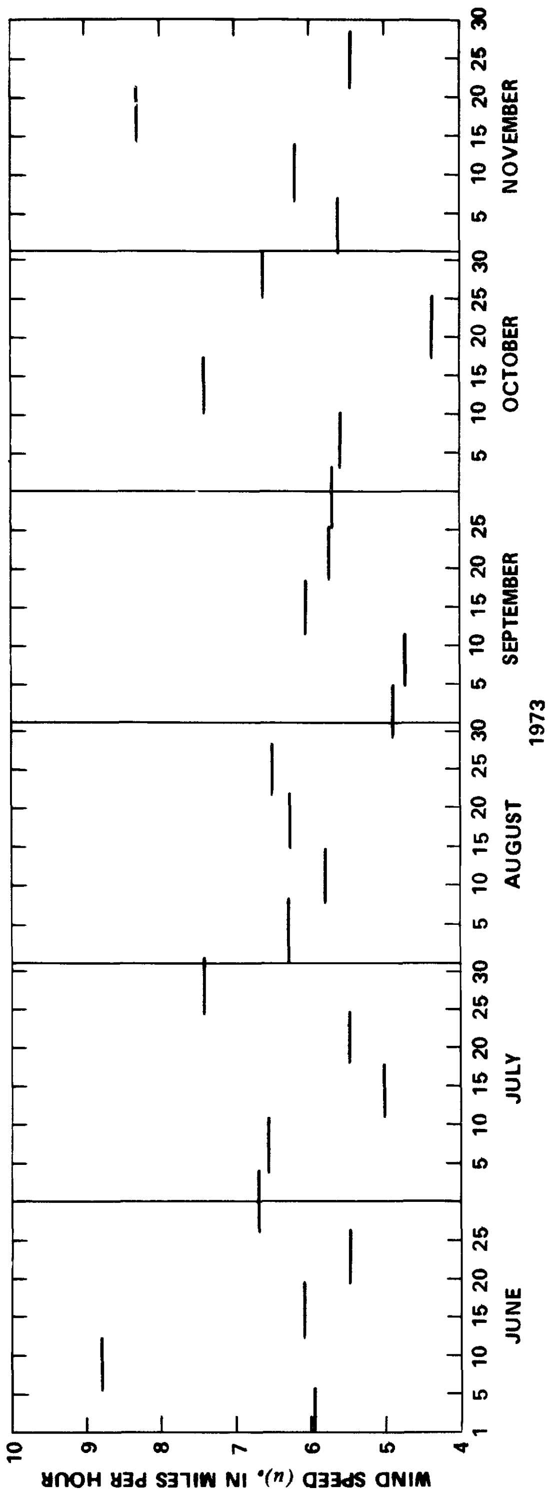

Figure 48.—Time graph of wind speeds, u, at Ralston Reservoir.

or pan exposure. The class-A pan evaporation from Ralston Reservoir is listed in table 15 with the mass-transfer evaporation.

Pan evaporation, along with ratios of reservoir to pan evaporation, is listed to illustrate that the coefficients vary widely from period to period and are not applicable for a short time interval. The seasonal ratio also is listed and, as can be seen, the ratios differ greatly from season to season and are significantly different from the common 0.7 coefficient. The ratios for Ralston Reservoir are varied and have been calibrated against mass-transfer evaporation data incorporating Harbeck's N values. In the event that it is determined that the pan method needs to be used to determine evaporation at this facility, the pan ratio needs to be calibrated against a more reliable method of evaporation determination, such as the energy-budget method.

SUMMARY AND CONCLUSIONS

It is generally acknowledged that the unbiased energy budget is the best method of computing evaporation. Problems associated with the energy budget are most apparent during the spring and fall of the year when the reservoirs are rapidly warming and cooling. This is caused by the averaging of the advected energy terms between thermal surveys. The problem is further compounded by rapid storage and release (filling and emptying) of water. The solution to this problem is to have more frequent thermal surveys, at greater expense.

The mass-transfer method calibrated against the energy budget is considered to be the second most reliable method, although the mass-transfer method tends to "smooth" abrupt differences observed in the energy-budget evaporation. This smoothing is due to the way the N value (mass-transfer coefficient) is determined by regression.

The pan method of computing evaporation is the least reliable of the three methods studied for this report. This is due to problems related to the pan environment, such as exposure and advected energy. Unless the pan is calibrated against data obtained by a reliable method, the use of pan data should be discouraged. Below are listed summaries of energy-budget and mass-transfer evaporation calculations.

Energy-Budget Evaporation Summary

Reservoir	1967 Total evaporation (cm)	1967 Season length (days)	1968 Total evaporation (cm)	1968 Season length (days)	1969 Total evaporation (cm)	1969 Season length (days)	1970 Total evaporation (cm)	1970 Season length (days)
Elevenmile Canyon---	85.8	182	70.4	166	73.5	168	69.3	126
Dillon-----	----	---	----	---	68.0	155	61.8	140
Gross------	----	---	----	---	----	---	----	---

Reservoir	1971 Total evaporation (cm)	1971 Season length (days)	1972 Total evaporation (cm)	1972 Season length (days)	1973 Total evaporation (cm)	1973 Season length (days)
Elevenmile Canyon----------	----	---	----	---	----	---
Dillon--------------------	54.3	133	----	---	----	---
Gross---------------------	----	---	59.6	162	62.7	180

Mass-Transfer Evaporation Summary

Reservoir	1967 Total evapo-ration (cm)	1967 Season length (days)	1968 Total evapo-radion (cm)	1968 Season length (days)	1969 Total evapo-ration (cm)	1969 Season length (days)	1970 Total evapo-ration (cm)	1970 Season length (days)
Elevenmile Canyon---	78.5	182	82.5	166	74.3	168	59.2	126
Dillon-----	----	---	----	---	67.8	155	58.7	140
Gross------	----	---	----	---	----	---	----	---
Antero-----	27.5	92	53.9	161	36.6	119	38.1	127
Cheesman---	48.2	176	49.0	168	39.8	161	39.8	133
Williams Fork-----	----	---	----	---	54.2	152	47.1	141
Ralston----	----	---	----	---	----	---	----	---

Reservoir	1971 Total evapo-ration (cm)	1971 Season length (days)	1972 Total evapo-ration (cm)	1972 Season length (days)	1973 Total evapo-ration (cm)	1973 Season length (days)
Elevenmile Canyon----------	65.2	139	68.3	153	69.3	191
Dillon--------------------	58.6	135	59.0	140	62.5	157
Gross---------------------	----	---	51.0	146	69.6	180
Antero--------------------	33.8	115	----	---	----	---
Cheesman------------------	41.1	147	40.2	147	49.8	190
Williams Fork-------------	45.4	119	42.6	147	45.3	155
Ralston-------------------	----	---	23.9	121	65.8	183

As the summaries above show, seasonal evaporation varies from reservoir to reservoir. Total yearly evaporation is not known because rafts were not in operation during the total open-water period. No attempts were made to measure losses during periods of ice cover, by sublimation, but these losses have been shown to be small (see Ficke, 1972).

The following summary shows the N values for mass-transfer computation of evaporation (equation 7). Since the Harbeck N (Harbeck, 1962) can be computed *a priori* it is a useful starting point when no other data are available; but as can be seen, the calibrated energy-budget N differs significantly and large errors in computed evaporation will result if the N value is not calibrated.

Summary of N values

Reservoir	Calibrated from energy budget	Harbeck N (varies)
Elevenmile Canyon--------	0.00800	0.00575
Dillon-------------------	.00796	.00577
Gross--------------------	.00690	.00636
Antero-------------------	-------	.00590
Cheesman-----------------	-------	.00610
Williams Fork------------	-------	.00600
Ralston------------------	-------	.00667

The evaporation from pans has long been thought of as a reliable way to estimate annual evaporation from lakes and ponds. The summary below shows the ratios of lake-to-pan evaporation for each reservoir, for the years 1967-73. As was stated previously, these values are from raw data and vary quite widely from the traditional "0.7" coefficient that has frequently been postulated. Again it must be stated that a ratio or coefficient is good only on an annual basis, if used at all, and then the value is only of marginal accuracy. The ratios vary depending on pan exposure, as well as reservoir exposure. Also, the coefficient is meaningless unless it has been calibrated with a reliable method of evaporation measurement.

Ratio of lake mass-transfer evaporation to pan evaporation[1]

Reservoir	Year						
	1967	1968	1969	1970	1971	1972	1973
Elevenmile Canyon[2]------	0.86	0.88	0.86	0.92	0.87	0.69	0.74
Dillon[2]----------------	----	----	.94	.74	.76	.82	.73
Gross[2]-----------------	----	----	----	----	----	.61	.55
Antero-------------------	.72	.58	.54	.49	.38	----	----
Cheesman-----------------	.55	.53	.50	.54	.51	.55	.40
Williams Fork------------	----	----	.65	.58	.58	.57	.55
Ralston------------------	----	----	----	----	----	.29	.48

[1]The ratios above, as noted earlier, are not based on evaporation for the total year, but on the length of season mentioned previously.

[2]Reservoirs for which energy budget has been calculated.

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