

ESTIMATING EVAPORATION
PRIOR TO RESERVOIR CONSTRUCTION

by

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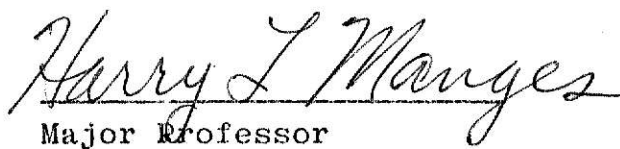
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INTRODUCTION

Evaporation measurement is of importance in many scientific fields. Reliable evaporation data are required for planning, designing and operating reservoirs, shipping canals and drainage systems (World Meteorological Organization, 1971).

As many scientists have stated, the loss of water by evaporation from a free water surface is a sizable amount. To cite an example, in the state of Oklahoma the estimated annual potential evaporation from free water surfaces varies from about 48 inches at the eastern edge of the state to 66 inches at the southwestern corner of the state (Meyer and Tor, 1962). Evaporation lowers the quality of water. As pure water evaporates, salts and other material are left behind. Thus, the concentration of the dissolved matter increases in the remaining stored water.

Considerable evaporation research has been done all over the world. However, there is no particular method that is internationally accepted for determining evaporation. Somehow the equations differ from one another. For instance the mass transfer empirical formulas developed in the U.S. and U.S.S.R. have coefficients of different form.

In nations where drought problems are severe, construction of reservoirs for storage of water is necessary. Evaporation must be predicted for proper reservoir design. Therefore, the aim of this study was to determine a procedure for estimating evaporation prior to the construction of a reservoir. The pro-

cedure must require a minimum of measured input parameters. To achieve this aim the author has classified his investigation into the following three main parts:

- a. Estimating evaporation from an energy budget with as few measured parameters as necessary.
- b. Estimating evaporation by the mass transfer method with water surface temperature estimated from climatological data.
- c. Estimating evaporation from Penman's potential evapotranspiration equation.

REVIEW OF LITERATURE

Water Budget Method

The water budget method is simply the measurement of all incoming and outgoing water so as to determine evaporation. Harbeck and Kenon (1952) expressed it algebraically as:

$$E = I - O - S \quad (1)$$

where

E = evaporation

S = change in reservoir storage

I = inflow

O = outflow

They observed that daily values are subject to errors, especially during spring and fall months when the effect of thermal expansion of the water in the reservoir results in a more or less systematic, but unavoidable error when measuring volume of water. However, the water budget is widely used to evaluate the performance of other equations for estimating evaporation.

Harbeck and Kenon (1952) reported daily evaporation results by the water budget for the 1950-51 Lake Hefner study. For one-third of the time the error was less than 5% and for three-fifth of the time it was less than 10%. Young (1947) reported a satisfactory water budget study of evaporation at 5500 acre Lake Elsinore in California for the years 1939 - 1941. The average

yearly evaporation for the three year period was 56.24 inches.

Although the water budget is a satisfactory method for determining evaporation, its use to estimate evaporation prior to the construction of a reservoir is impossible because of a lack of inflow, outflow and change in water storage measurements.

Energy Budget Method

The energy budget method is like the water budget method with all incoming and outgoing energy instead of water being measured. The difference must equal the change in stored energy of the reservoir. The energy budget method is based on the law of conservation of energy.

Schmidt (1915) and Angstrom (1920) used the energy budget method to compute evaporation. Budyko (1956) used the method to compute evaporation from both land and water surfaces of the entire earth and reported reasonable results.

Bowen (1926) expressed the energy budget method algebraically as:

$$I = S + LE (1 + R) \quad (2)$$

where

I = radiant energy integrated over any time interval (solar and sky radiation corrected for reflection, minus the back radiation)

LE = heat represented by the evaporation during the same time interval

$R(LE)$ = relatively small correction due to conduction and convection

S = heat represented by the change in temperature of the water

He stated that Equation 2 is an exact equation for any body of water that is thermally insulated on sides and bottom.

Anderson (1954), using the energy budget method, conducted an evaporation study at Lake Hefner. He algebraically expressed the energy budget as:

$$Q_S + Q_a + Q_v - (Q_r + Q_{ar} + Q_{bs} + Q_e + Q_h + Q_w) = Q_o \quad (3)$$

where

Q_S = solar radiation incident to the water surface

Q_a = incoming atmospheric radiation

Q_v = net energy advected into the lake by inflow and withdrawal

Q_r = reflected solar radiation

Q_{ar} = reflected atmospheric radiation

Q_{bs} = long-wave radiation emitted by the body of water

Q_e = energy used by evaporation

Q_h = energy conducted by the body of water as sensible heat

Q_w = energy advected in the evaporated water

Q_o = change in energy stored in the body of water

The use of Equation 3 was limited due to the fact that it was difficult to separate the energy conducted by the body of water as sensible heat, Q_h , from the energy used by evaporation, Q_e . However, Bowen (1926) found a solution for the above problem. He expressed the two terms as a ratio.

The Bowen ratio was found with the assumption that the process of evaporation or diffusion of water and the conduction or

diffusion of specific heat energy from the water surface into the same body of air is exactly the same. This assumption has been controversial among scientists. In fact some scientists still account for any discrepancy in evaporation results on the use of the Bowen ration. The Bowen ratio is expressed mathematically as:

$$R = \frac{CP}{1000} \left(\frac{T_o - T_a}{e_o - e_a} \right) \quad (4)$$

where

R = Bowen ratio, dimensionless

C = coefficient, mb/°C

P = atmospheric pressure, mb

T_o = water surface temperature, °C

T_a = air temperature, °C

e_o = saturation vapor pressure at water surface temperature, mb

e_a = air vapor pressure at two meters height, mb

The value of C in Equation 4 ranges from 0.58 to 0.66. Bowen concluded that under normal atmospheric conditions the value of C is approximately 0.61.

Utilizing the Bowen ratio, Q_h can be expressed in terms of Q_e as follows:

$$Q_h = R Q_e \quad (5)$$

where

Q_h = energy conducted by the body of water as sensible heat, cal/cm² - day

Q_e = energy used by evaporation, cal/cm²-day

The energy advected in the evaporated water can be expressed as:

$$Q_w = \frac{c Q_e T_e}{L} \quad (6)$$

where

T_e = temperature of the evaporated water (taken as the water surface temperature), °C

Q_w = energy advected in the evaporated water, cal/cm²-day

c = specific heat of water, cal/g °C

L = Latent heat of vaporization, cal/g

By substituting the above terms for Q_h and Q_w and rearranging the terms, Equation 2 is reduced to:

$$Q_e = \frac{Q_s + Q_a - (Q_r + Q_{ar} + Q_{bs} + Q_o - Q_v)}{1 + R + c \left(T_e / L \right)} \quad (7)$$

Anderson (1952) concluded that the energy method gave adequately accurate evaporation results for time intervals from 7 to 10 days. But for shorter time intervals, the results were subject to considerable error. This is due to the fact that the accuracy of temperature measurements is limited, thus affecting the evaluation of change in stored energy. The magnitude of error in measuring stored energy depends on the size of the reservoir.

Allen (1968) compared the energy budget method and the water budget method. He found that evaporation computed by the energy budget method exceeded the water budget evaporation for the majority of the observation periods. Excluding questionable data and considering the water budget evaporation as the standard, the

energy budget method overestimated the evaporation by 18 percent in 1965 and 24 percent in 1966. He found the relation of best fit to be:

$$E_{eb} = 0.07 + 0.93 E_{wb} \quad (1965 \text{ and } 1966) \quad (8)$$

where

E_{eb} = evaporation by energy budget method

E_{wb} = evaporation by water budget method

MASS TRANSFER METHOD

The mass transfer method is based on the fact that the driving force behind evaporation as described by Dalton (1798) is the vapor pressure difference between the water surface and the air. Scientists have made many attempts to relate evaporation to wind speed and vapor pressure deficit and many empirical equations have been developed.

The general form of the relationship is as shown below:

$$E = N U (e_o - e_a) \quad (9)$$

where

E = evaporation

N = a coefficient of proportionality or mass-transfer coefficient

U = wind speed

e_o = saturation vapor pressure corresponding to water surface temperature

e_a = vapor pressure of air

The mass transfer coefficient represents the variation of wind speed with height, size of lake, roughness of water surface, atmospheric stability, barometric pressure and density and viscosity of air. Despite the fact that it depends on many variables, Harbeck (1962) was able to relate the mass transfer coefficient to surface area of the lake as shown in Figure 1.

Equations 10 and 11 are empirical formulas developed in the United States and the U.S.S.R., respectively, and are reported to have yielded fairly reliable results (World Meteorological Organization, 1971). They are:

$$E = 0.131 U (e_o - e_a) \text{ and} \quad (10)$$

$$E = 0.13 (1 + 0.72 U) (e_o - e_a) \quad (11)$$

where

E = evaporation, mm

U = wind speed at two meters above water surface, m/sec

e_o = saturation vapor pressure corresponding to water surface temperature, mb

e_a = vapor pressure of air at a height of two meters, mb

Rohwer (1931) conducted evaporation studies in Colorado using an 85-foot diameter reservoir. He found the following empirical equation:

$$E = (0.44 + 0.118 W) (e_o - e_a) \quad (12)$$

where

W = ground wind speed, mph

E = evaporation, inches

e_a and e_o = as described above, inches of Hg

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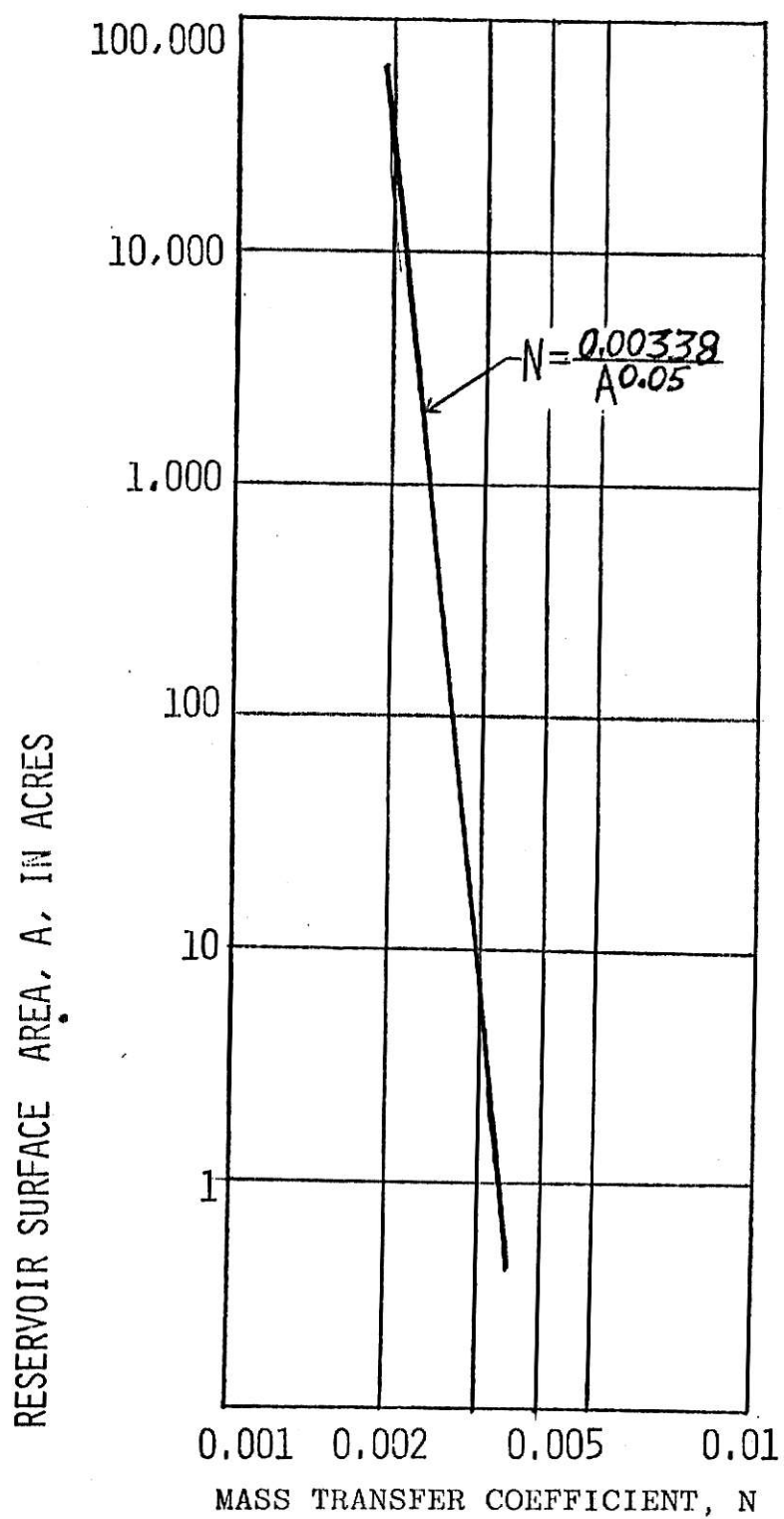


Figure 1. Relation Between Mass Transfer Coefficient, N, and Reservoir Surface Area (Figure reproduced from Harbeck, 1962)

Marciano and Harbeck (1954) developed an empirical equation from water budget evaporation, wind speed and vapor pressure difference for the 1950-51 Lake Hefner studies. The equation is:

$$E = 6.25 \times 10^{-4} U_8 (e_o - e_8) \quad (13)$$

where

E = evaporation, centimeters per 3 hours

U_8 = wind speed 8 meters above the water surface, knots

e_8 = vapor pressure of the air at 8 meters above the water surface, mb

e_o = vapor pressure of saturated air at the water surface, mb

Manges (1969) carried out an evaporation study at Stillwater, Oklahoma. He used a pond of one-fourth acre of surface area. His semi-empirical equation is:

$$E = \frac{N'}{T_o} D S_c^{1/3} \left(\frac{U_2}{\gamma} \right)^{0.78} (e_o - e_a) \quad (14)$$

where

E = evaporation, cm/day

D = daily average diffusion coefficient, cm^2/sec

T_o = daily average water surface temperature, $^{\circ}\text{K}$

S_c = daily average Schmidt number for air, dimensionless

U_2 = daily average wind speed at a height of 2 meters, cm/sec

γ = daily average kinematic viscosity of air, cm^2/sec

N' = mass transfer parameter, $^{\circ}\text{K sec}/\text{cm}^{.22}\text{-mb-day}$

e_o and e_a = as described above, mb

Penman's Potential Evapotranspiration Equation

Penman (1963) expressed a combined equation of aerodynamic and energy balance. His equation was reduced for potential evapotranspiration to :

$$E = \frac{\Delta (H) + E_a \gamma}{\Delta + \gamma} \quad (15)$$

where

E = evaporation from a free water surface, cm/day

Δ = slope of the saturation vapor pressure curve at air temperature, mb/°C

H = heat budget, cal/cm²-day

γ = constant in the wet and dry bulb psychrometer equation, mb/°C

E_a = an expression for the drying power of the air, involving wind speed and saturation vapor deficit, cm/day

He also described the drying power as:

$$E_a = 0.35 (0.5 + U/100) (e_a - e_d) \quad (16)$$

where

E_a = as above, mm/day

e_a = saturation vapor pressure at mean air temperature obtainable from standard tables, mm Hg

e_d = mean air vapor pressure, mm Hg

U = wind speed at 2 meters height, miles/day

INVESTIGATION

Objectives

The objective of the study was to determine a procedure for estimating evaporation from a site prior to the construction of a reservoir. The objective was met by evaluating the energy budget method, the mass-transfer method and Penman's potential evapotranspiration equation for estimating evaporation from climatological data.

Methods and Procedure

The research was conducted at the Ashland Agronomy Farm located approximately 9 miles south of Manhattan, Kansas. It was carried out in the spring of 1975 for the period April 8 to June 13. A tank, 2.74 meters in diameter and 1.22 meters deep, was used. The tank was buried in the ground except for the top 12 centimeters. Fig. 2 shows the setup of the experiment.

All necessary parameters were either measured or estimated to calculate evaporation by water budget, energy budget, and mass-transfer methods as well as Penman's equation. The parameters measured were:

1. Water surface elevation of the tank
2. Precipitation
3. Wind speed
4. Dry-bulb temperature of the air
5. Water surface temperature of the tank

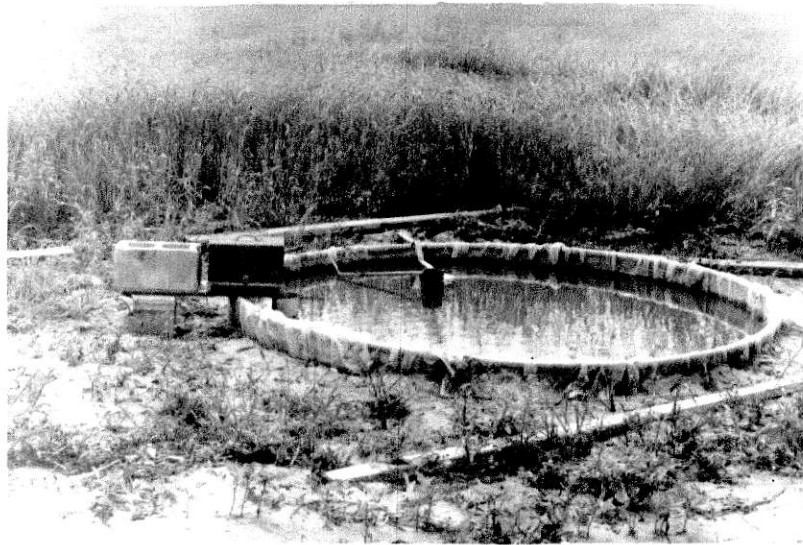


Figure 2. Experiment Setup

6. Short-wave incoming radiation
7. Tank temperature profile
8. Relative humidity
9. Atmospheric pressure

Water Surface Elevation

Water surface elevation was measured in a plastic pipe located halfway between the center and the edge of the tank. A hook-gauge that reads to a thousandth of an inch was used to determine the elevation of the water surface level. The water level in the tank was measured at 7 p.m. each day.

Wind Speed

Wind speed was measured by Casella anemometer set approximately 2 meters above the water surface elevation and recorded by a ME Kantral recorder.

For the period up to April 10 the anemometer was set to record the number of revolutions every 6 hours. Starting April 11, it was reset to record every 3 hours for the rest of the period of the experiment.

Air Temperature and Relative Humidity

In measuring air temperature a hygrothermograph was used. The hygrothermograph was placed approximately 2 meters above ground level. It was located on the campus of Kansas State University which is about 9 miles north of the site of the experiment. Hourly air temperature and hourly relative humidity were read from the hygrothermograph chart.

Water Surface Temperature

Water surface temperature was measured with a thermocouple located approximately half-way between the center and the edge of the tank. This was meant to give an average value of the water surface temperature. The thermocouple was attached to the bottom of a styrofoam float. Screws were screwed in at each corner of the bottom side of the styrofoam float to prevent the float from turning upside down and exposing the thermocouple to direct radiation. Thus, the water surface was measured at about one centimeter of depth. Temperature was recorded at one-hour intervals by a Honeywell Elektronik multipoint strip chart recorder.

Tank Temperature Profile

Tank temperature profile was measured at depth intervals of 10 centimeters, except for the top layer where the depth varied from 0-5 centimeters. The thermocouples were fixed inside the plastic tube as described above to avoid the direct radiation effects.

Solar Radiation

Incoming solar radiation was measured by an Eppley 180-degree hemispherical pyreheliometer. This instrument was located on the campus of Kansas State University. Solar radiation was recorded hourly and summed to get the daily total for the period from 7 a.m. to 7 p.m.

Data Collection and Analysis

This section includes the presentation of data that were measured and estimated. It also includes some discussion concerning the possibility of errors while measuring or computing the parameters.

Water Surface Elevation

Water surface elevation was read every day at 7 p.m. for the days when rainfall did not occur. The readings were taken in English units and converted to metric units. For some days the wind speed was high and wave action was unavoidable. Thus, two readings were taken and the average value recorded. This happened only for a few days.

Wind Speed

The number of revolutions that was recorded by the anemometer was summed for the 24 hour period 6 p.m. to 6 p.m., while all other evaporation parameters were measured for the 24 hour period 7 p.m. to 7 p.m. Difference in daily wind speed for the two 24 hour periods was deemed to be insignificant. The daily average wind speed is given in Table 1.

Air Temperatures and Relative Humidity

The dry-bulb air temperature was measured hourly. The values were read from a hygrothermograph chart and the average was computed for a 24 hour period. The daily average values are tabulated in Table 1. Daily average relative humidity was determined from a hygrothermograph chart like the dry-bulb air temperature. The daily average values are tabulated in Table 1. The wet-bulb air temperature that is shown in Table 1 was read from a psychrometric chart using daily average dry-bulb air temperature and daily average relative humidity.

Water Surface and Profile Temperatures

Water surface temperature and profile temperatures were determined from readings taken from a multipoint strip chart recorder calibrated to give millivolts output. This output was converted

Table 1. Daily Wind Speed, Relative Humidity, and Air Temperatures

Date	Wind Speed cm/sec	Relative Humidity %	Air Temperature	
			Dry Bulb °C	Wet Bulb °C
4/9	123.89	50	11.11	6.25
4/10	141.54	72	6.62	4.47
4/11	256.54	58	4.74	1.67
4/12	149.65	58	2.29	-0.44
4/16	264.90	66	16.07	12.50
4/17	389.31	49	21.61	15.00
4/20	196.54	50	10.46	6.11
4/21	263.76	38	17.34	10.00
4/22	296.05	64	15.91	12.11
4/23	476.70	64	22.96	18.11
4/24	300.46	59	19.66	14.89
4/25	212.10	71	16.64	13.61
4/26	479.47	69	20.91	15.56
4/27	456.73	73	20.67	17.22
4/28	510.56	42	18.45	11.56
4/29	204.41	40	16.62	9.72
4/30	267.16	44	14.28	8.33
5/1	191.80	48	12.36	7.22
5/2	293.37	56	15.02	10.56
5/5	147.67	48	20.95	13.89
5/6	314.84	60	22.96	17.44
5/7	391.65	39	17.16	9.44
5/8	190.89	43	16.64	10.11
5/9	195.04	55	18.73	12.78
5/27	124.27	60	17.76	12.94
5/31	71.68	60	14.63	10.44
6/4	272.68	54	25.88	15.28
6/5	118.53	65	24.19	19.44
6/6	108.30	55	24.77	18.22
6/12	245.83	53	20.67	14.79
6/13	114.15	54	24.52	18.22

to degrees centigrade by Equation 17 which is applicable for copper-constantan thermocouples:

$$T = 25.9 A - 0.66 A^2 \quad (17)$$

where

T = temperature, $^{\circ}\text{C}$

A = millivolts reading from the chart

The daily average water surface temperature was computed by averaging the hourly values for the 24 hour period 7 p.m. to 7 p.m. These values are shown in Table 2.

Although water profile temperatures were recorded every hour, the only values considered in this paper are 7 p.m. temperatures of each day. These values are tabulated in Table 3.

Atmospheric Pressure

Many researchers took atmospheric pressure as a constant for their respective area of research. In this paper daily average atmospheric pressures taken from the chart output of a micro-barograph were used. Originally it was read in inches of mercury and then converted to millibars. The daily average atmospheric pressure ranged from 957.65 mb to 984.07 mb and the average of the daily averages for the course of study was found to be 970.86 mb. The daily averages are recorded in Table 4.

Latent Heat of Vaporization

Latent heat of vaporization is another variable that can be considered a constant, but daily values were used in this study. It ranged from 580.9 to 590.5 cal/g. The daily values were computed by the use of Equation 18:

$$L = 595.9 - 0.545 T_o \quad (18)$$

Table 2. Daily Average Water Surface Temperature, Vapor Pressure Deficit, Latent Heat of Vaporization, and Average Atmospheric Pressure.

Date	Water Surface Temperature	Vapor Pressure Deficit	Latent Heat Of Vaporization	Atmospheric Pressure
	T_o	Δe	L	P
	°C	mb	cal/g	mb
4/9	12.11	7.511	589.3	969.8
4/10	11.24	6.366	589.8	978.0
4/11	9.85	7.183	590.5	984.1
4/12	11.03	8.968	589.9	984.4
4/16	15.58	5.642	587.4	969.2
4/17	18.27	8.262	585.9	957.7
4/20	14.02	9.670	588.3	971.2
4/21	16.08	10.747	587.1	976.6
4/22	16.76	7.511	586.8	965.8
4/23	19.91	5.221	585.0	966.5
4/24	20.64	10.764	584.7	969.8
4/25	20.06	9.991	585.0	969.2
4/26	20.76	7.386	584.6	965.8
4/27	21.50	7.851	584.2	961.7
4/28	19.42	13.633	585.3	964.4
4/29	19.48	15.069	585.3	963.8
4/30	19.12	14.970	585.5	969.8
5/1	17.99	13.728	586.1	978.0
5/2	17.04	9.859	586.6	975.6
5/5	20.37	12.018	584.8	963.1
6/5	21.72	9.171	584.1	961.0
7/5	21.15	17.461	584.4	965.8
8/5	20.95	16.645	584.5	969.2
9/5	21.36	13.539	584.3	975.3
5/27	23.86	17.388	582.9	975.9
5/31	21.39	15.478	584.2	971.2
4/6	25.35	14.318	582.1	963.4
5/6	26.36	14.718	581.5	968.5
6/6	27.41	19.335	581.0	970.9
6/12	24.49	17.810	582.6	973.9
6/13	27.53	20.155	580.9	971.2

Table 3. Temperature - Profile of the Water Body (°C) at 7 p.m.

Date	Surface	5 cm	15 cm	25 cm	35 cm	45 cm	55 cm	65 cm	75 cm	85 cm	95 cm	105 cm
4/8	12.03	12.03	12.03	12.03	11.85	11.39	10.89	10.38	10.25	10.25	10.25	10.13
4/9	15.68	15.55	15.30	13.16	12.15	11.65	11.65	11.52	11.52	11.52	11.52	11.27
4/10	10.38	10.38	10.38	10.38	10.51	10.51	10.51	10.51	10.38	10.38	10.38	10.38
4/11	10.81	10.81	10.89	10.89	10.89	10.89	10.81	10.81	10.63	10.63	10.63	10.51
4/12	14.42	14.30	14.30	12.53	11.52	11.52	11.52	11.33	11.33	11.33	11.27	11.14
4/15	14.67	14.67	14.67	14.67	14.55	12.79	12.03	11.90	11.90	11.90	11.52	11.52
4/16	21.04	20.92	19.05	16.06	14.55	14.42	14.42	14.42	14.30	14.30	14.06	13.92
4/17	20.30	20.30	20.30	10.05	17.06	16.56	16.56	16.43	16.43	16.43	16.43	16.31
4/19	13.67	13.67	13.67	13.67	13.79	13.79	13.79	13.79	13.79	13.79	13.79	13.79
4/20	16.56	16.68	16.68	15.80	14.67	14.55	14.55	14.55	14.42	14.42	14.30	14.17
4/21	19.30	19.18	18.56	16.81	16.06	16.06	15.93	15.93	15.93	15.93	15.93	15.93
4/22	18.43	18.43	18.43	18.43	17.31	16.56	16.43	16.43	16.31	16.31	16.18	16.18
4/23	24.13	24.13	23.89	22.16	20.17	19.05	18.80	18.80	18.68	18.68	18.56	18.31
4/24	20.67	20.67	20.67	20.67	19.80	19.80	19.80	19.68	19.68	19.68	19.55	19.30
4/25	21.41	21.41	21.41	21.41	20.92	20.92	20.92	20.79	20.79	20.67	20.55	20.30
4/26	22.03	22.03	21.91	21.91	21.91	21.91	21.91	21.91	21.91	21.41	21.04	20.67
4/27	21.04	21.04	21.04	21.04	21.04	21.04	21.04	21.04	21.04	21.04	20.79	20.79
4/28	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17
4/29	20.67	20.67	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79
4/30	19.43	19.43	19.43	19.43	19.55	19.55	19.55	19.68	19.68	19.68	19.55	19.55
5/1	18.31	18.31	18.31	18.31	18.31	18.31	18.31	18.31	18.31	18.31	18.31	18.18
5/2	17.43	17.56	17.55	17.56	17.56	17.56	17.56	17.56	17.56	17.56	17.56	17.56
5/4	20.67	20.67	20.79	20.79	20.79	20.79	20.67	20.55	20.55	20.30	20.30	20.17
5/5	22.16	22.16	21.16	21.16	21.16	20.92	20.92	20.79	20.79	20.79	20.79	20.67
5/6	22.16	22.16	22.16	22.16	22.16	22.16	22.16	22.16	22.16	22.16	22.03	21.66
5/7	22.03	22.03	22.03	22.03	22.03	22.03	22.03	22.03	22.03	22.03	22.03	22.03
5/8	21.91	21.91	21.91	22.03	22.03	22.03	22.03	22.03	22.03	22.03	21.91	21.91
5/9	22.40	22.28	22.40	22.40	22.40	22.40	22.28	22.28	22.28	22.28	22.16	22.16
5/26	23.76	23.76	23.76	23.76	23.76	23.76	23.76	23.76	23.89	23.89	23.89	23.89
5/27	24.50	24.50	24.50	24.50	24.38	24.26	24.26	24.01	24.01	24.01	24.01	23.89
5/30	21.54	21.54	21.54	21.54	21.54	21.54	21.54	21.54	21.54	21.54	21.54	21.54
5/31	22.78	22.78	22.78	22.53	24.63	24.50	24.50	24.50	24.26	24.26	24.26	24.26
6/3	29.52	29.40	29.40	26.47	24.50	23.39	22.65	22.16	20.55	20.55	20.55	20.17
6/4	26.47	26.47	26.47	22.22	25.24	24.50	24.01	23.52	22.65	22.65	22.40	21.91
6/5	29.52	29.40	29.40	28.91	27.08	26.10	25.49	25.12	24.50	24.50	24.26	23.76
6/6	29.52	29.40	29.40	29.28	27.69	27.20	26.34	25.98	25.73	25.73	25.49	24.75
6/11	25.24	25.12	25.12	25.12	24.26	23.89	23.76	23.52	23.52	23.52	23.52	23.39
6/12	27.94	27.69	27.69	26.22	25.24	24.75	24.63	24.63	24.63	24.50	24.50	24.01
6/13	30.13	30.13	30.01	28.18	26.96	26.47	26.47	26.22	26.22	26.22	26.10	25.73

where

L = latent heat of vaporization, cal/g

T_o = water surface temperature, °C

Vapor Pressure

The saturation vapor pressure of the air was taken as the saturation vapor pressure corresponding to the water surface temperature. These values were read from the Smithsonian Meteorological Tables (1951) for air over a water surface. In getting the saturation vapor pressure the daily average water surface temperatures were used. Runkles and others (1964) developed an equation from the vapor pressure tables in the Smithsonian Meteorological Tables. The equation is:

$$e_o = 5.979 + 0.5183 T_o + 0.005630 T_o^2 + 0.0005890 T_o^3 \quad (19)$$

where

e_o = daily saturation vapor pressure at water surface temperature, mb

T_o = daily water surface temperature, °C

The vapor pressure of the air was determined from daily dry-bulb temperature and daily relative humidity. The saturation vapor pressure at daily dry-bulb air temperature was read from the tables. Then air vapor pressure was determined by multiplying relative humidity by the saturation vapor pressure.

Daily vapor pressure can also be determined by Equation 20 (Smithsonian Meteorological Tables, 1951):

$$e_a = e_s - [0.000660 (1.0 + 0.00115 T_w)] P (T_a - T_w) \quad (20)$$

where

e_a = daily vapor pressure of the air, mb

e_s = daily saturation vapor pressure at the temperature
of wet-bulb, mb

T_w = daily wet-bulb temperature, °C

P = daily atmospheric pressure, mb

T_a = daily dry-bulb temperature, °C

The daily vapor pressure deficit is given in Table 2. It is the difference between the daily saturation vapor pressure at water surface temperature and the daily vapor pressure of the air.

Solar Radiation

Solar radiation was measured every hour. Daily solar radiation was calculated by adding the hourly values from 7 a.m. to 7 p.m. It is given in Table 4 in calories per square centimeter.

Reflected Solar Radiation

Reflected solar radiation was determined using Koberg's (1964) curves. First, clear sky radiation was read for Manhattan's latitude of 39 degrees. Then the ratio of measured and clear sky solar radiation was computed for each day to determine whether the prevailing condition was clear or cloudy. For a ratio greater than 0.80 the sky was considered clear and for a ratio less than 0.80 the sky was considered cloudy. Reflected solar radiation was calculated for each day. Daily values are given in Table 4. Equations to compute reflected solar radiation are also shown in Appendix A.

Table 4. Daily Incoming and Reflected Radiation

Date	Incoming Radiation		Reflected Radiation	
	Solar cal/cm ²	Atmospheric cal/cm ²	Solar cal/cm ²	Atmospheric cal/cm ²
4/9	618.8	584.8	34.5	17.5
4/10	207.6	551.9	19.0	16.5
4/11	480.9	520.7	33.5	15.6
4/12	638.6	495.6	41.7	14.9
4/16	587.7	668.2	40.5	20.0
4/17	614.0	725.6	41.5	21.8
4/20	562.4	577.2	39.5	17.3
4/21	582.5	645.9	40.0	19.4
4/22	304.2	663.5	25.0	19.9
4/23	511.6	773.3	40.0	23.2
4/24	494.9	712.2	40.5	21.4
4/25	613.1	682.5	41.0	20.5
4/26	280.8	746.8	24.0	22.4
4/27	99.0	748.3	11.0	22.4
4/28	662.3	667.4	42.5	20.0
4/29	559.5	639.8	36.0	19.2
4/30	649.6	616.1	42.0	18.5
5/1	466.7	584.8	32.5	17.5
5/2	308.4	628.4	25.5	18.9
5/5	530.9	699.7	34.5	21.0
5/6	496.4	752.5	34.0	22.6
5/7	700.9	631.7	43.5	18.9
5/8	650.7	631.4	42.5	18.9
5/9	565.4	678.7	36.0	20.4
5/27	561.6	671.9	36.0	20.2
5/31	545.5	628.2	36.0	18.8
6/4	482.6	772.8	33.0	23.2
6/5	719.5	758.3	44.0	22.7
6/6	603.8	759.8	37.5	22.8
6/12	715.1	710.6	45.0	21.3
6/13	662.5	756.2	42.0	22.6

Atmospheric Radiation

The incoming atmospheric radiation was computed using Brunt's (1944) equation. The equation treats the atmosphere as a gray body. Brunt expressed his equation as:

$$Q_a = (a + b \sqrt{e_a}) \sigma T_a^4 \quad (21)$$

where

Q_a = the radiation received, cal/cm²-day

σ = the Stefan-Boltzmann constant, (1176.48 x 10⁻¹⁰ cal/cm²-day °K)

T_a = the daily air temperature, °K

a = constant

b = constant

e_a = vapor pressure of the air, mb

The quantity ($a + b\sqrt{e_a}$) estimates the emissivity of the sky. The values for the constants were given by Wartena and others (1973). These values are given according to month and wind direction category as shown in Appendix B, Table 13. The atmospheric radiation given in Table 4 was computed using a and b constants according to month. Values of a are 0.619, 0.600 and 0.751 for April through June, respectively, and values of b are 0.056, 0.057 and 0.017 for April through June, respectively.

Reflected Atmospheric Radiation

Daily reflected atmospheric radiation is computed based on Anderson's (1954) conclusion that the emissivity of water is 0.970 for a water temperature range of 0 to 30 degrees centigrade. Thus, daily reflected atmospheric radiation, Q_{ar} , was calculated as 0.03 Q_a and is given in Table 4.

Water Surface Back Radiation

The long-wave radiation emitted by the water surface, Q_{bs} is given in Table 5. Daily back radiation was calculated using Equation 22:

$$Q_{bs} = 0.97 \sigma T_o^4 \quad (22)$$

where

Q_{bs} = daily back radiation, cal/cm²

0.97 = emissivity of water

$\sigma = 1176.48 \times 10^{-10}$, cal/cm²-day - °K⁴

T_o = daily water surface temperature, °K

Change in Stored Energy

Change in stored energy was computed for each increment of depth by the following equation:

$$q_o = C D (\rho_2 T_2 - \rho_1 T_1) \quad (23)$$

where

q_o = change in stored energy for the incremental depth,
cal/cm²

C = specific heat of water, taken as 1 cal/gm-°C

D = layer depth, cm

ρ_2 = density of water at T_2 , taken as 1 g/cm³

T_2 = average temperature for the incremental depths at the
end of the period, °C

ρ_1 = density of water at T_1 , taken as 1 g/cm³

T_1 = average temperature for the incremental depths at the
beginning of the period, °C

Temperature for the top and bottom of each layer at 7 p.m. were averaged to secure average temperature for each depth increment. The change in stored energy for the layers were summed

Table 5. Back Radiation, Change in Stored Energy,
Net Radiation and Bowen Ratio

Date	Back Radiation Q_{bs} cal/cm ² -day	Change in Stored Energy Q_o cal/cm ² -day	Net Radiation Q_n cal/cm ² -day	Bowen Ratio dimensionless
4/9	754.1	141.4	397.5	0.079
4/10	744.9	-207.2	-20.9	0.433
4/11	730.4	37.6	188.6	0.427
4/12	742.7	124.2	334.9	0.583
4/16	791.4	262.2	404.0	-0.051
4/17	821.4	206.5	454.9	-0.236
4/20	774.5	128.0	308.3	0.218
4/21	796.9	70.0	372.1	-0.070
4/22	804.5	49.0	118.3	0.067
4/23	840.0	320.4	381.7	-0.344
4/24	874.7	-14.2	270.5	0.054
4/25	841.7	102.2	392.4	0.202
4/26	849.8	80.6	131.4	-0.012
4/27	858.4	-72.9	-44.5	-0.062
4/28	834.4	-85.6	432.8	0.042
4/29	835.1	63.4	309.0	0.112
4/30	831.0	-126.8	374.2	0.191
5/1	818.2	129.2	183.3	0.245
5/2	807.6	-85.4	84.8	0.122
5/5	845.3	39.2	329.8	-0.028
5/6	861.0	118.8	331.3	-0.079
5/7	854.3	-9.6	415.9	0.135
5/8	852.0	-3.9	368.7	0.153
5/9	856.8	332.7	330.9	0.116
5/27	886.3	41.3	291.0	0.209
5/31	857.1	250.6	261.8	0.259
6/4	904.2	24.5	295.0	-0.022
6/5	916.5	31.6	494.6	0.087
6/6	929.4	81.1	373.9	0.081
6/12	893.8	130.3	501.6	0.127
6/13	930.9	191.7	423.2	0.088

to give the daily change in stored energy which is given in Table 5.

Net Radiation

Net radiation, Q_n , is also given in Table 5. It was computed using Equation 24:

$$Q_n = Q_s + Q_a - (Q_r + Q_{bs} + Q_{ar}) \quad (24)$$

where

Q_n = daily net radiation, cal/cm²

Bowen Ratio

Bowen ratio was determined using Equation 4. Water surface and air temperatures were taken as daily averages. Daily Bowen ratio values are given in Table 5.

RESULTS

Estimation of Water Surface Temperature

Estimation of water surface temperature is first considered for it is the parameter that is involved in estimating evaporation prior to construction of a reservoir. Estimation was processed using data given in Table 6 (Manges 1965). It was found that daily water surface temperature is related to daily dry- and wet-bulb air temperatures and relative humidity. That is water surface temperature has a straightline relationship to the quantity $\left(\frac{T_w + T_a}{2} + (RHT_a)^{.25} \right)$ as shown in Figure 3. A linear regression analysis of water surface temperature versus the quantity above gave the equation:

$$T_{oe} = 5.98 + 0.74 \left(\frac{T_w + T_a}{2} + (RHT_a)^{.25} \right) \quad (25)$$

$$R^2 = 0.83$$

where

T_{oe} = daily estimated water surface temperature, °C

T_w = daily wet-bulb air temperature, °C

T_a = daily dry-bulb air temperature, °C

RH = daily relative humidity, in fraction

R^2 = regression coefficient

Equation 25 was used to compute water surface temperature of the test tank. The values are given in Table 7 and shown in Figure 4. As shown in Table 7 as well as in Figure 4, Equation

Table 6. Daily Dry-Bulb Air Temperature (T_a), Daily Wet-Bulb Air Temperature (T_w), Daily Water Surface Temperature (T_o), and Relative Humidity (RH).*

Date	T_a °C	T_w °C	T_o	RH
8/14	26.56	21.23	25.52	0.63
8/15	24.68	20.57	25.54	0.70
8/16	24.13	20.67	25.35	0.74
8/17	25.57	22.23	25.83	0.64
8/18	29.51	21.69	25.89	0.51
8/21	26.95	22.11	27.74	0.67
8/24	26.76	22.99	28.76	0.70
8/25	29.23	23.43	28.18	0.62
8/26	31.09	23.81	27.69	0.55
8/27	29.88	23.06	27.24	0.57
8/28	24.10	21.10	27.08	0.75
8/29	25.82	21.37	26.81	0.68
8/30	28.57	22.84	26.59	0.62
9/1	19.19	15.30	23.82	0.68
9/2	21.03	16.49	23.57	0.64
9/5	27.07	23.03	25.97	0.72
9/9	27.65	22.63	27.19	0.66
9/10	25.12	21.41	26.43	0.73
9/14	31.58	21.52	25.31	0.41
9/15	28.53	21.47	25.15	0.54
9/16	29.61	21.72	24.32	0.51
9/23	16.59	13.51	21.37	0.73
9/24	12.12	9.29	18.37	0.71
9/25	14.29	11.78	17.39	0.76
9/26	18.42	16.10	18.10	0.80
9/27	19.41	16.28	18.71	0.74
9/28	20.05	16.60	19.53	0.72
9/29	21.23	18.28	20.37	0.77
10/1	13.07	9.87	16.97	0.67
10/2	14.64	11.09	17.50	0.67
10/3	14.94	12.74	17.66	0.80
10/4	16.37	14.28	17.74	0.81
10/5	15.14	12.69	17.95	0.77
10/6	14.36	12.54	15.59	0.79
10/7	18.84	14.73	17.92	0.66
10/8	18.59	14.38	18.64	0.64
10/9	20.90	15.89	19.26	0.60
10/10	21.57	16.29	19.90	0.59
10/13	18.79	14.91	17.43	0.63
10/14	21.26	18.35	18.47	0.77
10/15	21.16	18.50	19.51	0.79
10/20	14.29	11.24	18.41	0.71
10/21	11.86	8.79	16.13	0.69
10/22	10.93	6.94	13.80	0.58
10/23	14.74	11.03	14.13	0.65

*Table reproduced from Manges's Ph.D. Thesis, 1965

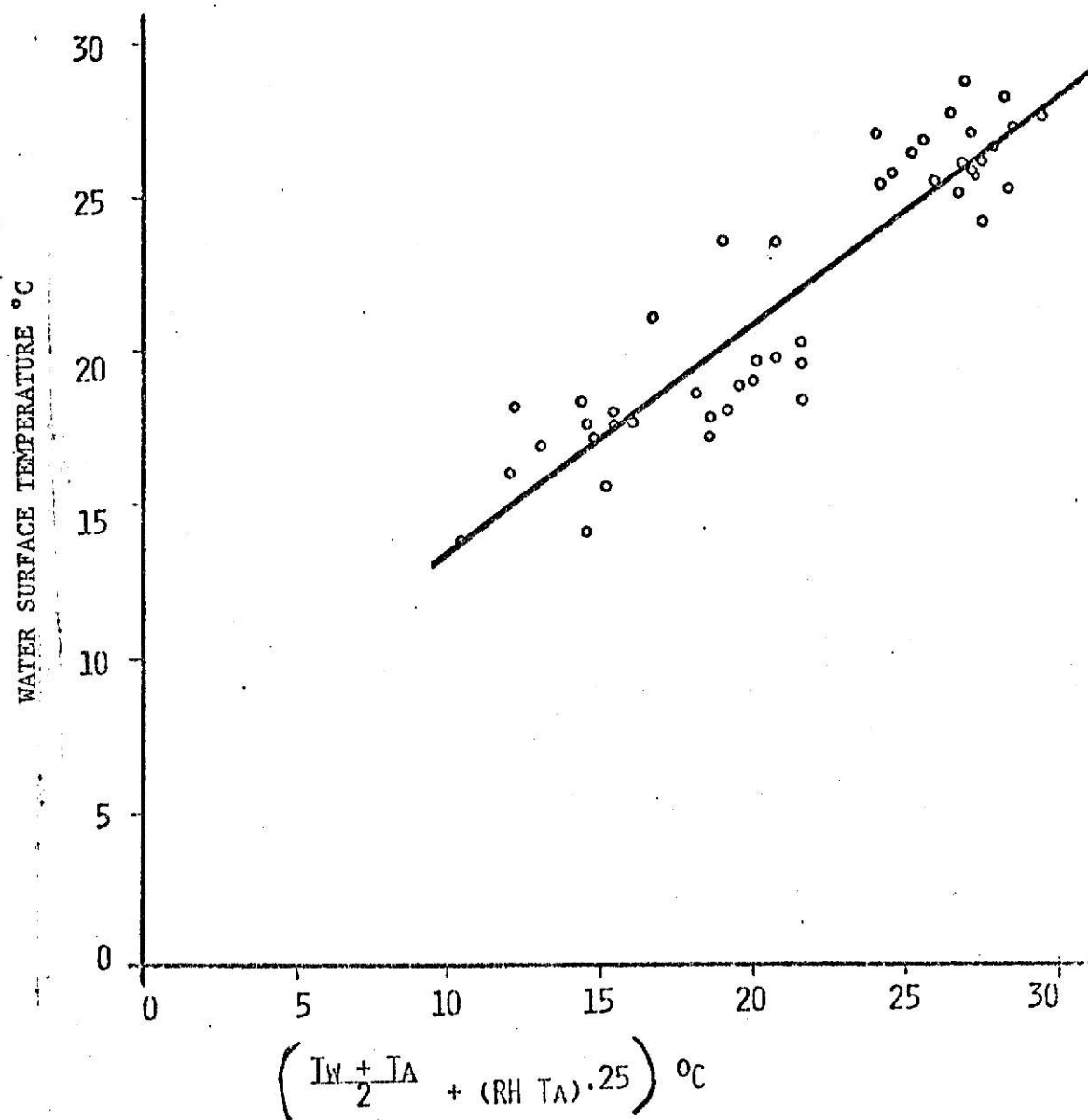


Figure 3. Water Surface Temperature Versus $\left(\frac{T_w + T_a}{2} + (RH \ T_a) \cdot .25 \right) ^\circ C$

Table 7. Measured and Estimated (by eq. 25) Water Surface Temperatures and the Difference Between the Two.

Date	Measured Water Surface Temperature*	Estimated Water Surface Temperature	Measured Minus Estimated
	T_o °C	T_{oe} °C	$T_o - T_{oe}$ °C
4/9	12.11	13.54	-1.43
4/10	11.24	11.18	0.06
4/11	9.85	9.30	0.55
4/12	11.03	7.46	3.57
4/16	15.58	17.89	-2.31
4/17	18.27	20.86	-2.59
4/20	14.02	13.23	0.73
4/21	16.08	18.47	-2.39
4/22	16.76	17.67	-0.91
4/23	19.91	22.49	-2.58
4/24	20.64	20.13	0.51
4/25	20.06	18.54	1.52
4/26	20.76	20.92	-0.16
4/27	21.50	21.46	0.04
4/28	19.42	18.32	1.10
4/29	19.48	16.91	2.57
4/30	19.12	15.52	3.60
5/1	17.99	14.38	3.61
5/2	17.04	16.70	0.34
5/5	20.37	20.19	0.18
5/6	21.72	22.35	-0.63
5/7	21.15	17.01	4.14
5/8	20.95	17.09	3.86
5/9	21.36	18.96	2.40
5/27	23.86	18.68	5.18
5/31	21.39	16.53	4.86
6/4	25.35	22.64	2.71
6/5	26.36	23.60	2.76
6/6	27.41	23.31	4.10
6/12	24.49	20.42	4.07
6/13	27.53	23.21	4.32

* Taken from table 3.

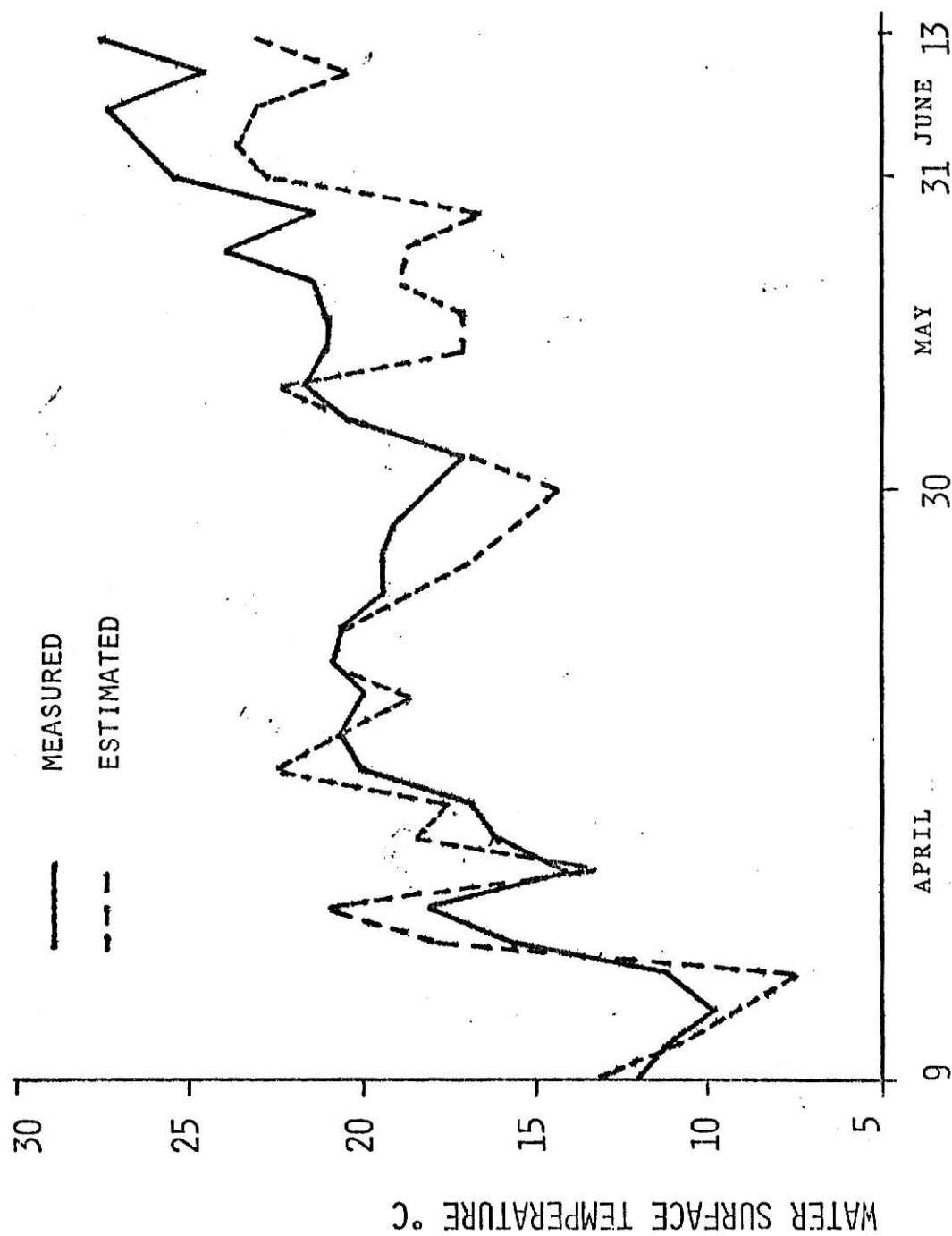


Figure 4. Measured and Estimated Water Surface Temperature for the Period of the Experiment.

25 underestimated the daily water surface temperatures for most of the period. It overestimated for 8 out of 31 days.

Water Budget Method

Evaporation by the water budget method was calculated on a daily basis from difference in water surface elevations. Daily evaporation by this method is included below. These values are used for evaluating the performance of other methods for estimating evaporation.

Energy Budget Method

Evaporation by the energy budget method was computed using Equation 7 divided by the latent heat of vaporization. It was assumed that specific heat of water was unity and water surface temperature was taken as the temperature of the evaporated water. Daily evaporation was calculated using measured water surface temperature.

A linear regression analysis of daily evaporation by the water budget versus that of the energy budget was carried out. The results were as shown by Equation 26a:

$$E_{eb} = 0.14 + 0.56 E_{wb} \quad (26a)$$

$$R^2 = 0.22 \quad S. E. = 0.19$$

where

E_{eb} = daily evaporation by the energy budget, cm

E_{wb} = daily evaporation by the water budget, cm

Evaporation calculated by a one day energy budget underestimated evaporation as compared to that by water budget. The mean evaporation rates for energy budget and water budget were

0.35 cm/cay and 0.38 cm/day respectively.

Evaporation by the energy budget method was also calculated using two consecutive day averages. The two day averages were calculated for the following parameters:

1. Solar radiation, Q_s
2. Dry-bulb air temperature, T_a
3. Water surface temperature, T_o
4. Air vapor pressure, e_a

Change in stored energy was calculated by the same procedure as for a daily energy budget, but temperature readings taken every 48 hours were used rather than those taken every 24 hours.

Using the average values for the four parameters enumerated above, the rest of the terms in the energy budget equation were determined. Their values are given in Table 8.

Evaporation by the water budget was averaged for two days and compared to that calculated by the energy budget. These values are given in Table 9 and shown in Figure 5. The mean evaporation rate by the two methods was found to be equal. It was 0.37 centimeters per day.

A linear regression analysis of evaporation by the energy budget method versus that by the water budget gave Equation 26b:

$$E_{eb} = 0.06 + 0.85 E_{wb} \quad (26b)$$

$$R^2 = 0.57, \quad S. E. = 0.12$$

An attempt was made to express the energy budget equation in terms of parameters that do not need the actual presence of a reservoir. The estimated water surface temperature can be used in the energy equation, but no successful means was found

Table 8. Incoming, Reflected, and Back Radiations, and Change in Stored Energy
for two Consecutive Days.

Month	Dates	Incoming Radiation		Reflected Radiation		Back	Change in Stored Energy
		Solar	Atmospheric	Solar	Atmospheric	Radiation	
		Q_s cal/cm ²	Q_a cal/cm ²	Q_r cal/cm ²	Q_{ar} cal/cm ²	Q_{bs} cal/cm ²	Q_o cal/cm ²
April	9 - 10	413.2	568.3	30.5	17.0	720.4	34.1
	11 - 12	559.8	508.1	39.5	15.2	667.2	79.2
	16 - 17	600.9	699.2	41.0	21.0	827.8	232.0
	20 - 21	572.5	610.9	39.8	18.3	773.2	141.5
	22 - 23	407.9	718.0	32.5	21.5	834.6	183.5
	24 - 25	554.0	697.2	39.0	20.9	820.0	41.0
	26 - 27	189.9	745.5	20.0	22.4	850.2	0.3
	28 - 29	610.9	653.7	41.5	19.6	813.2	-7.1
May	1 - 2	387.6	606.8	29.0	18.2	770.9	-99.5
	5 - 6	513.6	726.6	34.2	21.8	863.8	74.3
	7 - 8	675.8	631.6	43.0	18.9	806.0	-12.9
June	4 - 5	601.1	765.1	38.5	23.0	900.4	131.4
	12 - 13	706.8	733.3	43.6	22.0	871.3	156.0

Table 9. Comparison of Evaporation Rate by Water Budget and Energy Budget Methods.*

Month	Date	Measured Evaporation by Water Budget	Estimated Evaporation by Energy Budget
		cm/day	cm/day
April	9 - 10	0.26	0.24
	11 - 12	0.30	0.30
	16 - 17	0.26	0.35
	20 - 21	0.36	0.33
	22 - 23	0.12	0.10
	24 - 25	0.35	0.49
	26 - 27	0.35	0.07
	28 - 29	0.68	0.61
May	1 - 2	0.34	0.36
	5 - 6	0.52	0.41
	7 - 8	0.61	0.66
June	4 - 5	0.40	0.44
	12 - 13	0.33	0.52

* Average Evaporation rates for 2 days

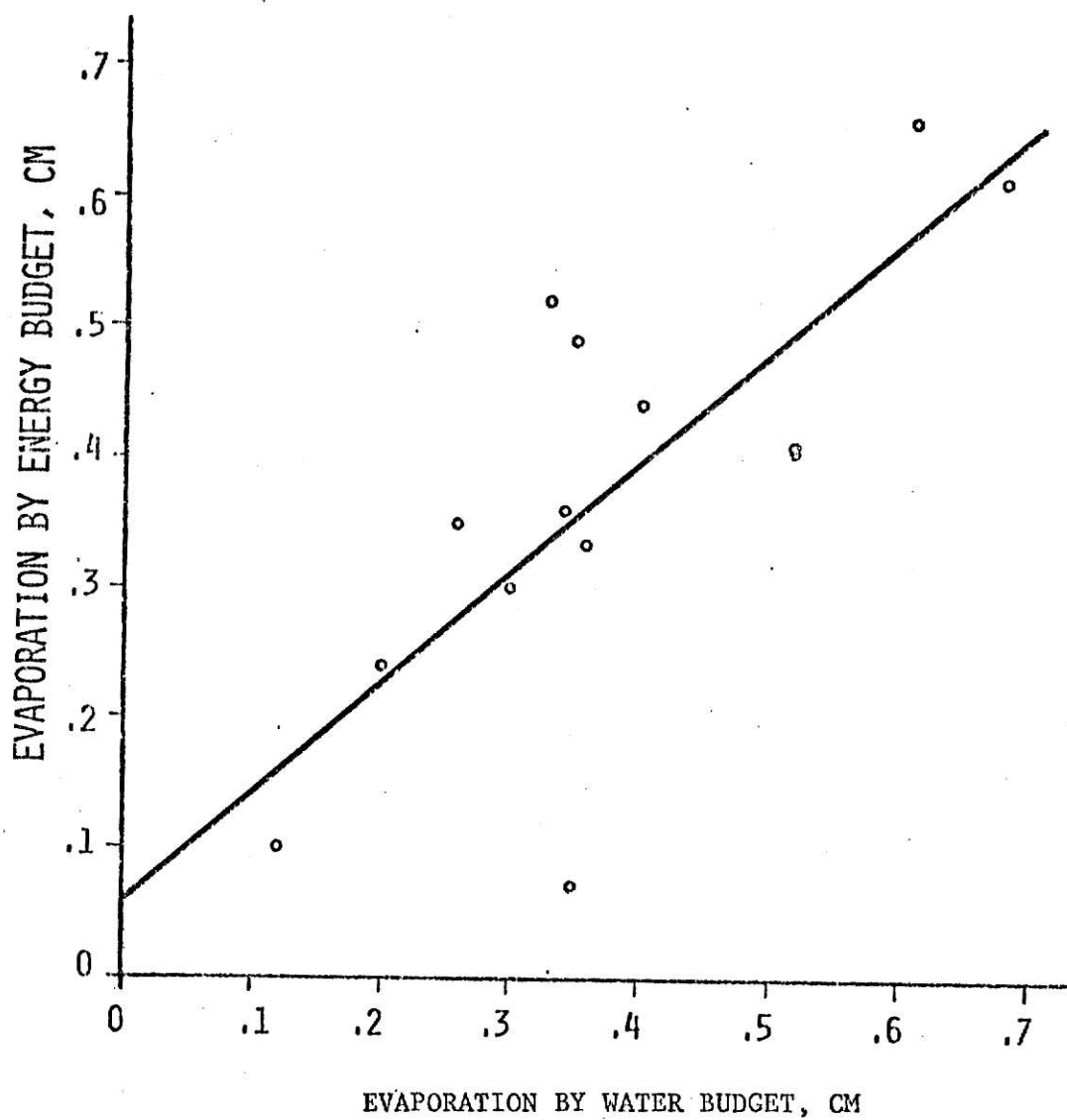


Figure 5. Comparison of Evaporation by the Energy Budget with Evaporation by the Water Budget for Two Days Average.

to estimate change in stored energy. Thus, use of the energy budget for estimating evaporation prior to reservoir construction is not possible.

Mass Transfer Method

Evaporation was calculated by the mass transfer method using wind speeds given in Table 1 and vapor pressure deficits given in Table 2. Vapor pressure deficits were determined from measured water surface temperatures. It was assumed that the mass transfer equation had a form like that of Equation 9 except the power of U was unspecified. From a non-linear search technique, the mass transfer coefficient and the power for the wind speed were found to be 0.0024 and 0.48, respectively, as shown in Equation 27a:

$$E = 0.0024 U^{.48} (e_o - e_a) \quad (27a)$$

$$R^2 = 0.90, \quad S. E. = 0.140$$

where

E = daily evaporation, cm

U = wind speed at 2 meters height, cm/sec

e_o = saturation vapor pressure at water surface temperature, mb

e_a = air vapor pressure at 2 meters height, mb

The power for wind speed in this equation is smaller than those found in previous studies. This could possibly be attributed to the presence of growing wheat beside the tank during the period of study.

Some researchers found the power for wind speed to be near 0.80 while others found it to be 1.0. Coefficients given by the method of least squares:

$$E = 0.00039 U^{.80} (e_o - e_a) \quad (27b)$$

$$R^2 = 0.88, \quad S. E. = 0.153$$

$$E = 0.00012 U(e_o - e_a) \quad (27c)$$

$$R^2 = 0.85, \quad S. E. = 0.170$$

Evaporation calculated by Equations 27a, 27b, and 27c are given in Table 10. Figure 6 shows the difference in evaporation computed by the three equations from the water budget. There appears to be little difference in the accuracy of the equations in estimating evaporation.

Equations 27a, 27b, and 27c were used to calculate evaporation but saturation vapor pressure was taken at estimated water surface temperature given in Table 7 instead of at measured water surface temperature. Calculated evaporation is given in Table 11. Figure 7 shows the difference in evaporation computed by the three equations from that of the water budget. Figures 8, 9 and 10 show cumulative evaporation calculated by Equations 27a, 27b, and 27c compared with water budget evaporation.

A linear regression analysis of evaporation calculated by Equations 27a, 27b, and 27c using estimated water surface temperature compared with water budget evaporation was carried out. The results were as follows:

Table 10. Evaporation Calculated by Water Budget and
Mass Transfer Method with Measured Water
Surface Temperature

Date	Evaporation by Water Budget cm/day	Evaporation Calculated by Eq. 27a cm/day	Evaporation Calculated by Eq. 27b cm/day	Evaporation Calculated by Eq. 27c cm/day
4/9	0.14	0.18	0.14	0.11
4/10	0.25	0.16	0.13	0.11
4/11	0.11	0.25	0.24	0.23
4/12	0.48	0.24	0.19	0.17
4/16	0.25	0.20	0.19	0.19
4/17	0.27	0.34	0.39	0.40
4/20	0.40	0.29	0.26	0.24
4/21	0.32	0.37	0.37	0.35
4/22	0.07	0.27	0.28	0.28
4/23	0.17	0.24	0.29	0.31
4/24	0.37	0.40	0.40	0.40
4/25	0.33	0.31	0.29	0.26
4/26	0.30	0.34	0.41	0.44
4/27	0.40	0.35	0.42	0.45
4/28	0.91	0.65	0.79	0.87
4/29	0.44	0.46	0.42	0.38
4/30	0.62	0.52	0.52	0.50
5/1	0.52	0.41	0.36	0.33
5/2	0.15	0.36	0.37	0.36
5/5	0.47	0.31	0.26	0.22
5/6	0.57	0.35	0.36	0.36
5/7	0.53	0.73	0.82	0.85
5/8	0.68	0.49	0.44	0.40
5/9	0.54	0.40	0.36	0.33
5/27	0.36	0.42	0.33	0.27
5/31	0.32	0.32	0.21	0.15
6/4	0.44	0.50	0.50	0.49
6/5	0.35	0.35	0.27	0.22
6/6	0.43	0.44	0.32	0.26
6/12	0.37	0.60	0.57	0.55
6/13	0.29	0.47	0.35	0.29

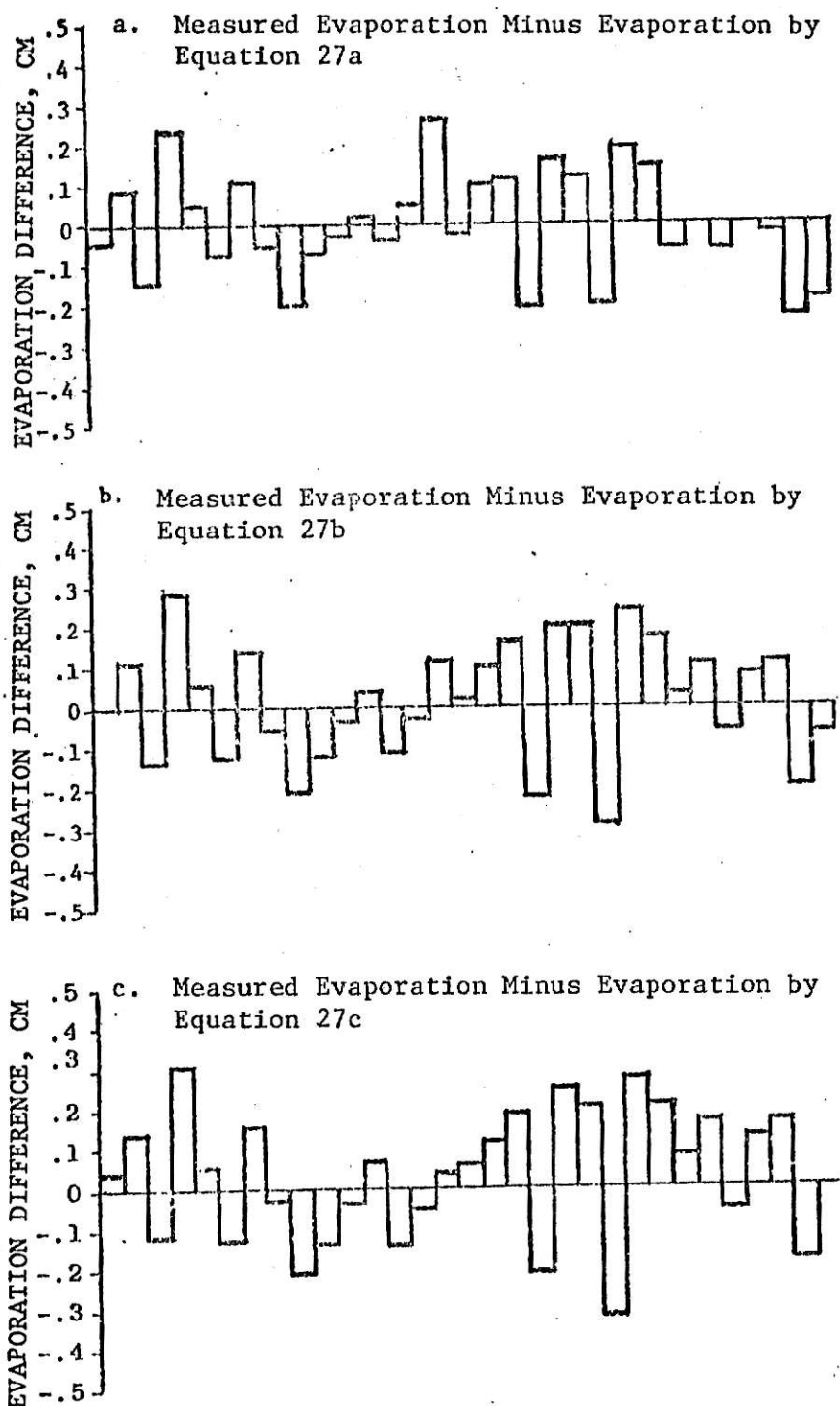


Figure 6. Daily Evaporation Difference by Mass Transfer Equations 27a, 27b and 27c (with measured water surface temperature) from Evaporation by Water Budget.

Table 11. Evaporation by Mass Transfer Method
with Estimated Water Surface Temperature

Date	Evaporation Calculated by Eq. 27a cm/day	Evaporation Calculated by Eq. 27b cm/day	Evaporation Calculated by Eq. 27c cm/day
4/9	0.22	0.16	0.13
4/10	0.16	0.13	0.11
4/11	0.23	0.22	0.21
4/12	0.16	0.13	0.11
4/16	0.29	0.29	0.27
4/17	0.50	0.55	0.56
4/20	0.27	0.24	0.21
4/21	0.48	0.46	0.43
4/22	0.32	0.32	0.31
4/23	0.43	0.50	0.53
4/24	0.37	0.37	0.36
4/25	0.25	0.22	0.20
4/26	0.35	0.42	0.44
4/27	0.35	0.41	0.43
4/28	0.58	0.69	0.74
4/29	0.36	0.32	0.29
4/30	0.37	0.36	0.34
5/1	0.28	0.25	0.22
5/2	0.35	0.35	0.33
5/5	0.31	0.25	0.21
5/6	0.39	0.40	0.38
5/7	0.50	0.54	0.55
5/8	0.34	0.30	0.26
5/9	0.30	0.27	0.23
5/27	0.23	0.17	0.14
5/31	0.20	0.13	0.09
6/4	0.34	0.33	0.31
6/5	0.23	0.17	0.14
6/6	0.26	0.19	0.15
6/12	0.37	0.35	0.33
6/13	0.28	0.20	0.16

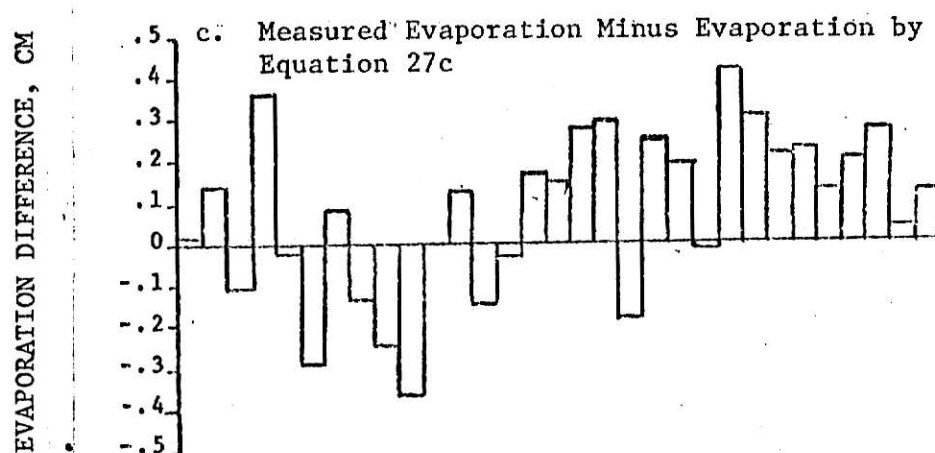
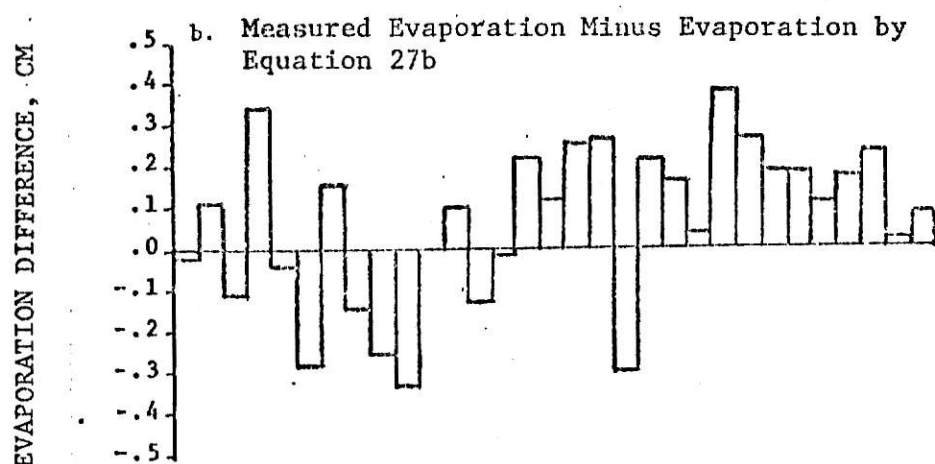
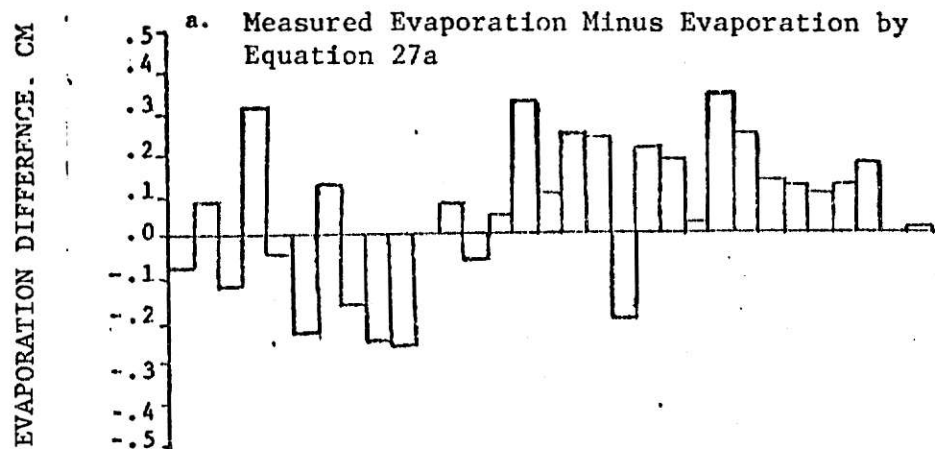


Figure 7. Daily Evaporation Difference by Mass Transfer Equations 27a, 27b and 27c (with estimated water surface temperature) from Evaporation by Water Budget

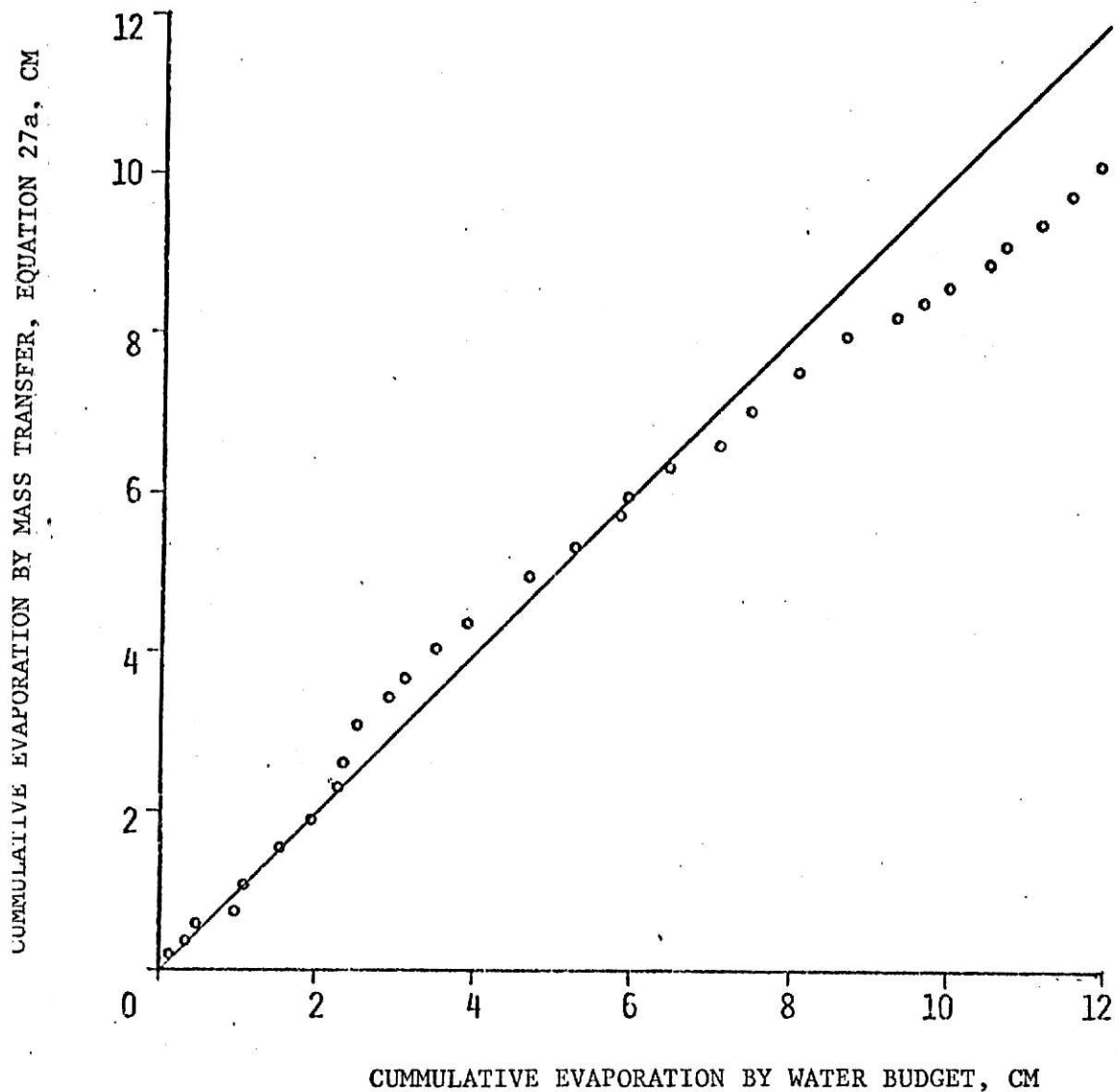


Figure 8. Comparison of Cumulative Evaporation by Mass Transfer Equation 27a (with estimated water surface temperature) with that by the Water Budget.

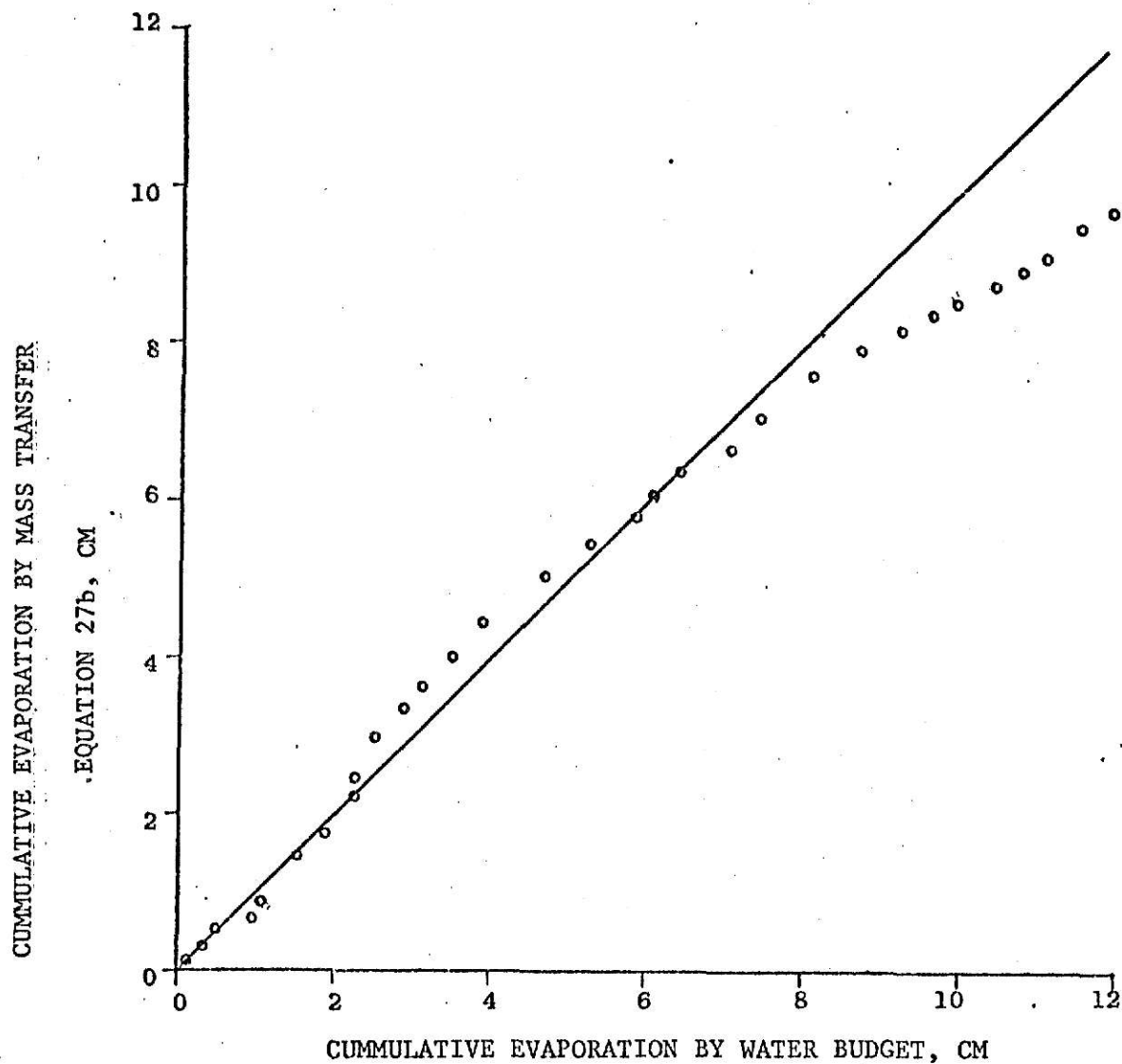


Figure 9. Comparison of Cumulative Evaporation by Mass Transfer Equation 27b (with estimated water surface temperature) with that by the Water Budget.

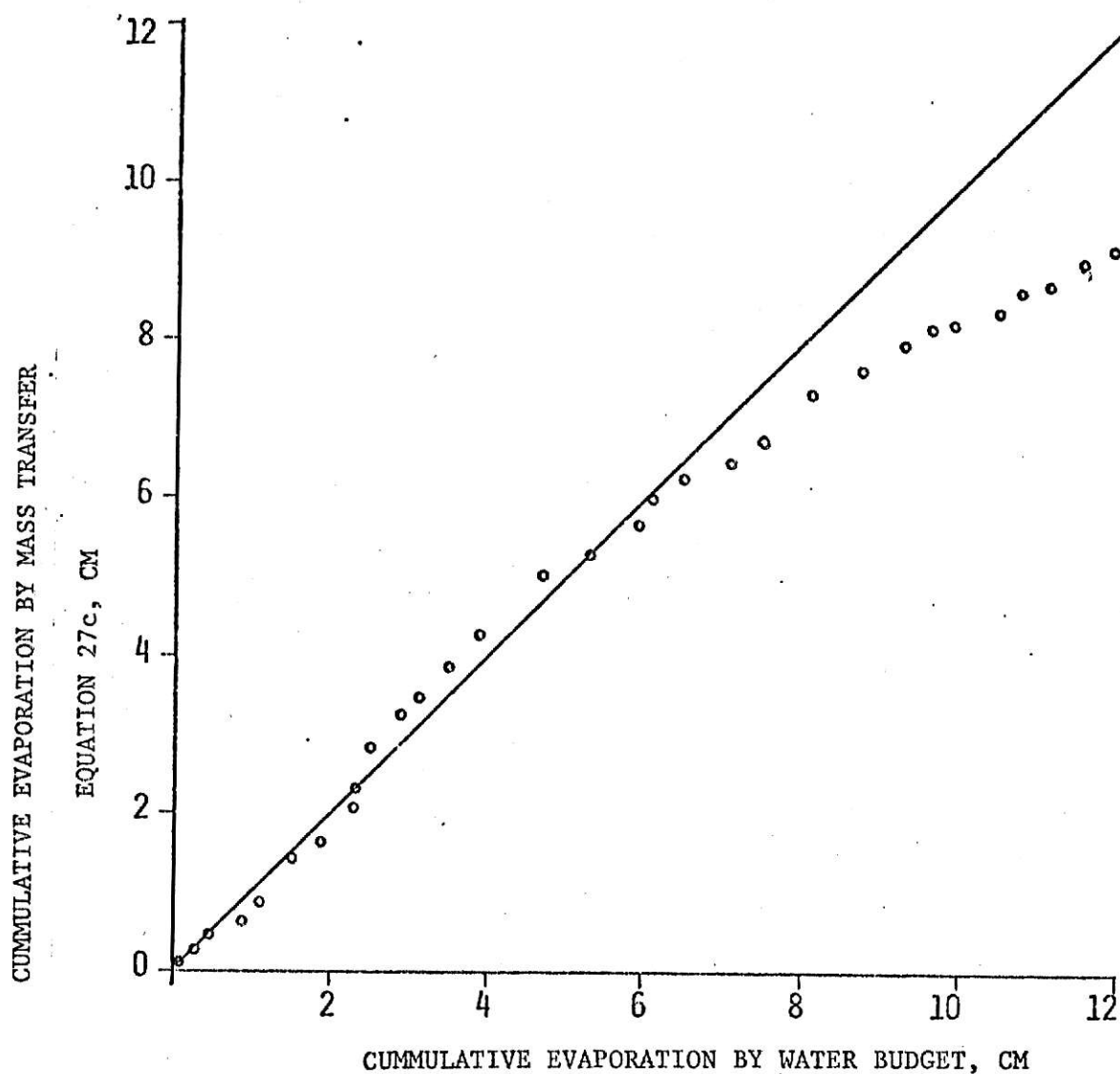


Figure 10. Comparison of Cumulative Evaporation by Mass Transfer Equation 27c (with estimated water surface temperature) with that by the Water Budget.

$$E E_{27a} = 0.738 E_{wb} \quad (28a)$$

$$R^2 = 0.84 \quad S. E. = 0.142$$

$$E E_{27b} = 0.719 E_{wb} \quad (28b)$$

$$R^2 = 0.79 \quad S. E. = 0.162$$

$$E E_{27c} = 0.685 E_{wb} \quad (28c)$$

$$R^2 = 0.75 \quad S. E. = 0.173$$

where

$E E$ = daily evapoation calculated with estimated water surface temperature, cm

For Equations 28a, 28b, and 28c the regression coefficients and the standard errors were found to be about the same. It was also observed that differences in evaporation calculated by the three different equations are small.

Penman's Potential Evapotranspiration Equation

Equation 15 was used to calculate evaporation from the tank. The heat budget, H , in this equation was replaced by daily net radiation, Q_n , as computed by Equation 24 minus the daily change in stored energy (Table 5) and heat flux to soil. This value was divided by daily latent heat of vaporization to convert calories per square centimeter per day to centimeters of water per day. The heat flux to the soil was taken to be zero on daily basis as suggested by Penman (1963). The drying power of air, E_a , was calculated by Equation 15. Δ and γ were read from tables given by Monteith (1973) with daily air temperature

as given in Table 1. The daily values were used in calculating daily potential evaporation.

The daily evaporation rates from Penman's equation are given in Table 12. For most of the observation, Penman's equation overestimated the daily evaporation rate as compared to that of the water budget. It was found that the mean evaporation rate was 0.42 cm/day for Penman's equation and 0.38 cm/day for the water budget.

Daily evaporation by the energy budget method is also included in Table 12 for the purpose of comparisons. Cumulative evaporation for Penman's equation and the energy budget methods versus cumulative evaporation by the water budget are shown in Figure 11.

Table 12. Daily Evaporation by Water Budget,
Penman's Equation and Energy Budget

Date	Evaporation by Water Budget cm/day	Evaporation by Penman's Budget cm/day	Evaporation by Energy Budget cm/day
4/9	0.14	0.37	0.40
4/10	0.25	0.26	0.22
4/11	0.11	0.30	0.22
4/12	0.48	0.28	0.22
4/16	0.25	0.31	0.25
4/17	0.27	0.54	0.53
4/20	0.40	0.33	0.25
4/21	0.32	0.58	0.54
4/22	0.07	0.25	0.11
4/23	0.17	0.28	0.15
4/24	0.37	0.51	0.45
4/25	0.33	0.44	0.40
4/26	0.30	0.25	0.08
4/27	0.40	0.22	0.05
4/28	0.91	0.93	0.82
4/29	0.44	0.44	0.37
4/30	0.62	0.73	0.70
5/1	0.52	0.21	0.07
5/2	0.15	0.44	0.25
5/5	0.47	0.47	0.49
5/6	0.57	0.43	0.38
5/7	0.53	0.75	0.62
5/8	0.68	0.57	0.54
5/9	0.54	0.14	0.01
5/27	0.36	0.38	0.34
5/31	0.32	0.09	0.01
6/4	0.44	0.47	0.45
6/5	0.35	0.66	0.70
6/6	0.43	0.46	0.45
6/12	0.37	0.60	0.55
6/13	0.29	0.38	0.35

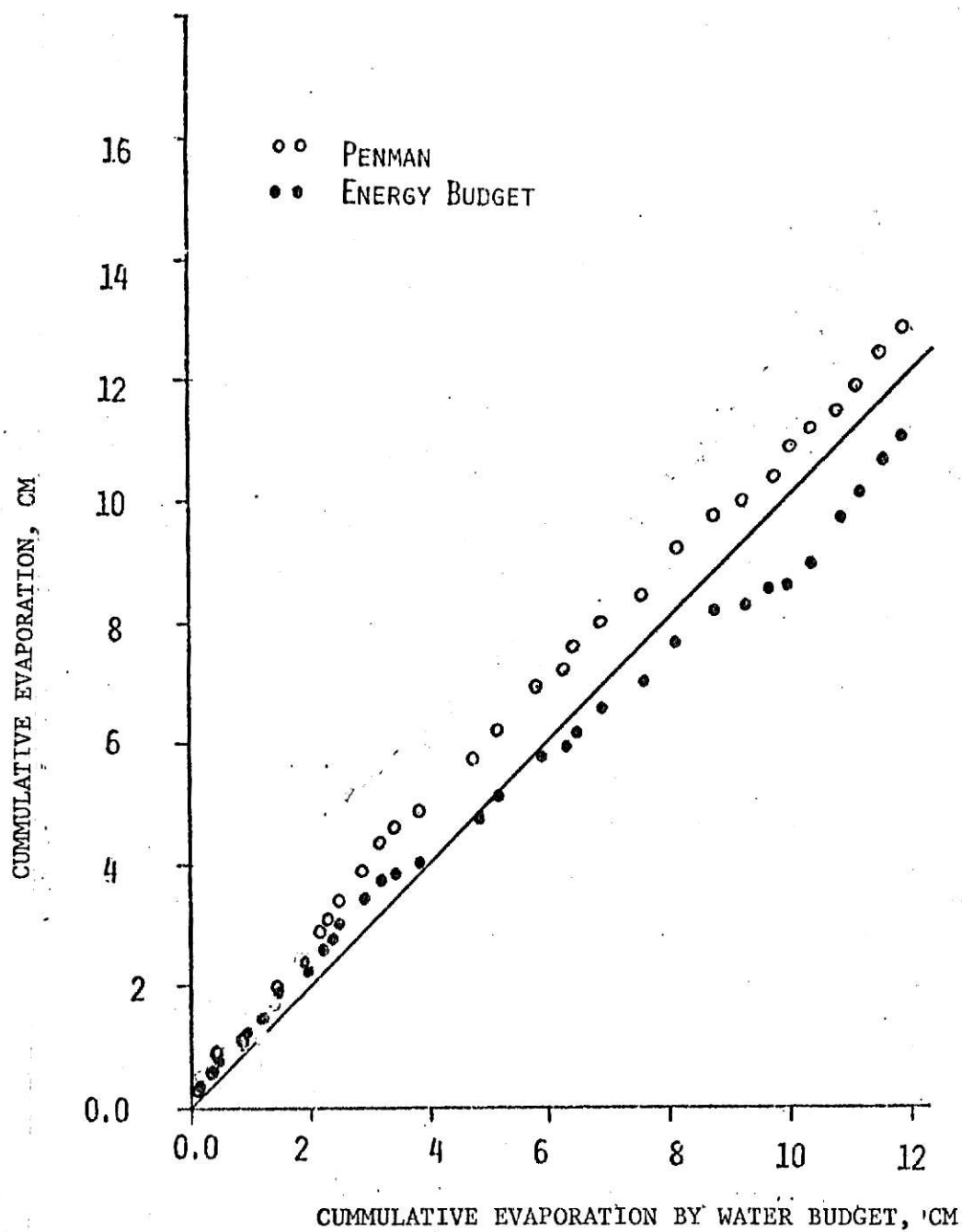


Figure 11. Curves Comparing Cumulative Evaporation by Penman's Equation and Energy Budget... with Cumulative Evaporation by Water Budget.

DISCUSSION

An estimate of evaporation from a proposed water storage reservoir can be quite useful in the hydrological design of the structure. The energy budget method, the mass transfer method and Penman's potential evapotranspiration equation were evaluated for estimating evaporation from climatological data.

Water Surface Temperature

Water surface temperature is an evaporation parameter that must be determined from indirect measurements. Equation 25 was developed from water surface temperature data taken in Oklahoma during August through October. Water surface temperatures were estimated by the above equation using parameters measured during March through May at the evaporation tank. Despite the fact that the data used to evaluate the coefficients of Equation 25 were from a different location and time of year than this study, estimated water surface temperatures compared favorably with measured temperatures.

The author is aware that the data used for determining the estimating equation were few covering a short range of conditions. A long range study covering a wide range of temperatures is recommended to verify or modify the estimating equation.

Energy Budget Method

The energy budget method did not estimate evaporation accurately on a daily basis but it gave relatively good results

on a 2 - day basis. Anderson (1952) stated that because of limits in the accuracy of the temperature measurements, considerable error may occur in evaluating the change of energy storage over time intervals of a few days. Thus, he suggested that adequate evaporation determinations can be attained for time intervals of the order of 7 to 10 days. In addition, errors were introduced in estimating long-wave radiation.

An attempt was made to relate the change in stored energy to other variables that do not involve the water body or that can be estimated. No such relationship was found. The closest relationship found but not included in this paper was an inadequate straight line relationship between daily change in stored energy and daily change in water surface temperature.

Mass Transfer

Three mass transfer equations were found which adequately estimated evaporation from the tank using estimated water surface temperatures. Exponents of the wind speed in the equations varied from 0.48 to 1.0.

The mass transfer coefficient must be estimated before the mass transfer equation can be used to estimate evaporation for a specific reservoir. Values of the coefficient are available in the literature for various sizes of reservoirs under varying climatic conditions. Use of the mass transfer equation with wind speed to the 1.0 power is recommended because mass transfer coefficients are available for this form of an equation.

Penman's Equation

Daily evaporation determined by this equation was found to vary from water budget evaporation. This could be due to the assumption that heat flux to the soil on a daily basis is zero. However, cumulative evaporation by this equation compared well to that by the water budget.

Penman's equation can be used to estimate evaporation prior to the construction of a reservoir provided the net energy available for evaporation can be estimated. Water surface temperature and change in stored energy are necessary to evaluate net energy. A procedure was developed to estimate water surface temperature from climatological data but no successful method was found for estimating change in stored energy. Therefore, Penman's equation like the energy budget cannot be used for estimating evaporation prior to reservoir construction.

CONCLUSIONS

Results from this study indicate:

1. Water surface temperature of a water storage reservoir can be estimated reasonably in terms of dry-and wet-bulb air temperatures and relative humidity.
2. The energy budget method does not give reasonable estimates of daily evaporation but on cumulative average evaporation it gave reasonable results.
It cannot be used to estimate evaporation without temperature measurements to determine change in stored energy.
3. The mass transfer method is adequate to estimate evaporation using estimated water surface temperatures.
4. Penman's equation gave a reasonable estimate of cumulative evaporation. However, it cannot be used to estimate evaporation without measurements to determine change in stored energy.

SUMMARY

With the increase in population growth, drought problems and industrialization, water resource management is becoming more important. Thus, the study of evaporation is timely.

In poor nations where evaporation data are not available, rough estimations are acceptable. Especially if it can be done with a minimum of measured climatological data.

An evaporation study was conducted on a 2.74 meters diameter and 1.22 meters deep tank. The tank was sunk in the ground to avoid rapid weather fluctuations so as to given conditions similar to a natural reservoir.

The purpose of this study was to determine a procedure for estimating evaporation from a site prior to the construction of a water storage reservoir. Such a procedure will be useful in planning, designing and constructing the reservoir. The energy budget method, mass transfer method and Penman's potential evapotranspiration equation were evaluated. Estimated evaporation using climatological data only was compared with water budget evaporation.

To achieve the above objectives, the water surface temperature must be estimated from climatological data. Water surface temperature was found to have a straight line relationship as shown by the equation:

$$T_{oe} = 5.98 + .74 \left(\frac{T_w + T_a}{2} + (RH T_a)^{0.25} \right) \quad (25)$$

where

T_{oe} = daily water surface temperature, °C

T_w = daily wet-bulb air temperature, °C

T_a = daily dry-bulb air temperature, °C

RH = daily relative humidity

The energy budget did a poor job of estimating evaporation on a daily basis. However, estimates for two day periods were acceptable. No relationship was found to adequately predict change in stored energy for a body of water from climatological data. As a result, the energy budget method cannot be used to estimate evaporation prior to the construction of a reservoir.

The following three mass transfer equations were found to estimate evaporation:

$$E = 0.0024 U^{.48} (e_o - e_a) \quad (27a)$$

$$E = 0.00039 U^{.8} (e_o - e_a) \quad (27b)$$

$$E = 0.00012 U (e_o - e_a) \quad (27c)$$

Estimated evaporation for all three equations, using Equation 25 to estimate water surface temperature, compared favorably with water budget evaporation. With any of the mass transfer equations, the coefficient for any given planned reservoir must be determined.

Penman's potential evapotranspiration equation overestimated evaporation from the experimental tank. The equation depends

on parameters which require a body of water to be present so that change in stored energy can be measured.

SUGGESTIONS FOR FUTURE RESEARCH

The estimation of water surface temperature for estimating evaporation with no reservoir present requires further study. In evaluating the coefficients in the equation, a wide range of data from different locations and different periods of the year must be considered so the resulting equation will have general application.

In order for the energy budget method to be used for evaporation determination from limited climatological data, further study of change in stored energy is necessary. A relationship between change in stored energy of a reservoir and measured climatological data must be found before the energy budget can be used to estimate evaporation prior to the construction of a reservoir.

A further study of the use of Penman's equation to determine evaporation from a free water surface prior to reservoir construction is also advisable. Needed is a relationship between climatological data and change in stored energy as stated above for the energy budget.

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A P P E N D I C E S

A P P E N D I X A

Computation of Reflected Solar Radiation *

$$Q_{sc} = 741.266 + 2.7247 \text{ Ed} - 0.018895 \text{ Ed}^2 - 0.00010389 \text{ Ed}^3 + \\ 0.00000041474 \text{ Ed}^4$$

where

Q_{sc} = clear sky radiation, cal/cm²-day

Ed = number of days since April 30

$$\frac{Q_s}{Q_{sc}} \geq 0.8 \quad \text{Clear sky}$$

$$\frac{Q_{sm}}{Q_{sc}} < 0.8 \quad \text{Cloudy sky}$$

For clear sky

$$Q_r = 0.70588 + 0.13888 Q_s - 0.19325 \times 10^{-3} Q_s^2 + \\ 0.15027 \times 10^{-6} Q_s^3 - 0.46334 \times 10^{-10} Q_s^4$$

For cloudy sky

$$Q_r = 0.57456 + 0.11661 Q_s - 0.14142 \times 10^{-3} Q_s^2 + \\ 0.99272 \times 10^{-7} Q_s^3 - 0.28180 \times 10^{-10} Q_s^4$$

where

Q_s = measured solar radiation, cal/cm²-day

Q_r = reflected solar radiation, cal/cm²-day

* Equation fitted to Koberg's curves for clear sky.

A P P E N D I X B

Values for the Constants in Brunt's Equation

Table 13. The Coefficients a and b with Their Respective Standard Deviation in Equation 22 Calculated According to Month and per Wind Direction Category.*

	a	sa	b(mb ^{-1/2})	sb
Wind Direction Category				
1	0.669	0.010	0.039	0.007
2	0.765	0.023	0.012	0.008
3	0.688	0.038	0.038	0.013
4	0.682	0.035	0.045	0.011
5	0.650	0.034	0.053	0.011
6	0.663	0.029	0.044	0.010
7	0.703	0.020	0.032	0.006
Month				
February	0.663	0.024	0.046	0.010
March	0.661	0.035	0.045	0.016
April	0.619	0.039	0.056	0.014
May	0.600	0.081	0.057	0.026
June	0.751	0.054	0.017	0.015
July	0.601	0.190	0.064	0.055
August	0.653	0.050	0.049	0.014
September	0.731	0.620	0.030	0.018
October	0.739	0.026	0.029	0.009
November	0.747	0.035	0.023	0.015
Year**	0.678		0.041	

* Table reproduced from Warenta, L. and others 1973

** Without the months of January and December

ESTIMATING EVAPORATION
PRIOR TO RESERVOIR CONSTRUCTION

by

TESFAI GHERMAZIEN

B.S., Haile Sellassie I University, 1972

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas
1975

ABSTRACT

Lack of water resource management is a major cause for the starvation that many nations are facing at present. Methods for estimating evaporation prior to construction of water storage reservoirs are needed for wise water resource management. Evaporation estimation methods must require the measurement of a minimum number of parameters at a minimum cost.

An evaporation study was established near Manhattan, Kansas. Sufficient parameters were measured to estimate evaporation by the energy budget method, the mass transfer method and Penman's potential evapotranspiration equation. Performance of these methods were evaluated by comparing calculated evaporation with measured evaporation by a water budget.

Prior to construction of a reservoir, all evaporation parameters must be determined from climatological data. A relationship between water surface temperature and wet-and dry-bulb air temperature and relative humidity was established from research conducted in Oklahoma. Water surface temperature is needed when estimating evaporation by the energy budget and the mass transfer methods.

No way was found to express change in stored energy for a body of water without direct measurement. Thus, the energy budget method cannot be used to estimate evaporation without the reservoir in place.

The mass transfer method successfully estimated evaporation using climatological data. Equations with the power of wind speed of 0.48, 0.80 and 1.0 all performed equally well. The equation with wind speed power of 1.0 is recommended as a better estimate of the mass transfer coefficient for the equation of this form can be made from the published literature.

Penman's equation requires climatological data along with water surface temperature and change in stored energy as inputs to estimate evaporation. Although a method was found to estimate water surface temperature, no satisfactory method was found to estimate change in stored energy. Therefore, Penman's equation cannot be used to estimate evaporation without the reservoir in place..

It is recommended that research be conducted to find a satisfactory method of estimating change in stored energy so that both the energy budget and Penman's equation can be used for estimating evaporation prior to construction of the reservoir.