DETERMINATION OF EVAPORATION AT LAKE HEFNER BY ENERGY AND WATER BUDGET METHODS--1965

By

WILLIAM EARL FRY

Bachelor of Science
Oklahoma State University
Stillwater, Oklahoma
1965

Submitted to the faculty of the
Graduate College
of the Oklahoma State University
in partial fulfillment of the
requirements for the degree
of
MASTER OF SCIENCE
May, 1967

DETERMINATION OF EVAPORATION AT LAKE HEFNER BY ENERGY AND WATER BUDGET METHODS--1965

F. R. Crow
Thesis Adviser

James E. Garton

N. N. Durham
Dean of the Graduate College

PREFACE

Though evaporation has been occurring since the beginning of time, the measurement of the quantity is still an inexact science, allowing only the evaluation of estimates of the quantity. This thesis reports part of the results of an over-all evaporation suppression investigation conducted cooperatively by the United States Bureau of Reclamation and Oklahoma State University. Two methods were used to determine evaporation, the water budget method acting as the control and the energy budget method being compared to the control, for the purpose of evaluating the coefficient in the mass transfer equation for determining evaporation.

This research study was conducted by the Agricultural Engineering Department, Oklahoma State University, under Contract Number 14-06-D-5629 with the Bureau of Reclamation of the United States Department of the Interior.

The author gratefully acknowledges Franklin R. Crow, Associate Professor of Agricultural Engineering, for counsel and guidance in performing the experiment, analyzing the results, and preparing this thesis.

Appreciation is expressed to Professor E. W. Schroeder, Head of the Agricultural Engineering Department, and Dr.

James E. Garton, Professor of Agricultural Engineering, for their encouragement to enter into the graduate program.

Acknowledgments are due the personnel of the Water Conservation Branch of the United States Bureau of Reclamation for providing instrumentation, technical, and financial assistance.

Jim Allen, Research Assistant, is acknowledged for his assistance in analyzing the water budget data.

Appreciation is also due to other faculty and staff members for suggestions and assistance, the departmental draftsmen for the drafting of the charts and graphs, and the author's fellow graduate candidates for their remarks on modern research techniques.

The author gratefully acknowledges the support of his wife, Nita, and his children in his endeavor, and also acknowledges the support of the Heavenly Father.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Water, next to the air we breathe, is our most important natural resource. Therefore, it should follow that any loss of this vital element would be of considerable importance in view of the increasing demand for water for agricultural and municipal needs.

In the Report of the President's Water Resources Policy Commission (1950), the position was taken that "while use of water is increasing and there are areas of deficient water supply for present and future needs, the overall situation reveals an adequate supply for the Nation's needs".

It may be true that the Nation as a whole has plenty of water. However, the distribution is such that the arid areas of the West, where the agricultural water demand is very high, experience precipitation amounts that are considerably less than the 30 inch national average.

One method of conserving precipitation runoff has been to catch and store it in surface reservoirs. A water loss problem exists with this type of storage. Large areas of free water surface are exposed to factors conducive to evaporation, mainly wind and radiation. Bellport (1964) stated that the average annual evaporation from fresh water bodies in the 17 western states is estimated to be more than 14 million acre-feet. A higher estimate of approximately 23 1/2 million acre-feet had been given by Meyer (1962).

Concern over the evaporation losses from Lake Mead, the largest man made reservoir in the world, caused the United States Bureau of Reclamation to participate with several other Government agencies in a program of evaporation investigations. A classic evaporation study took place at Lake Hefner in 1950-51 in which instrumentation and evaporation theory were tested and evaluated. Subsequent evaporation studies were made at Lake Hefner in 1958, Lake Sahuaro in 1960, Lake Cachuma in 1961, and Pactola Reservoir in 1964 as a part of evaporation suppression investigations. A one-year evaporation study was also made at Elephant Butte Reservoir in 1963-64. The evaporation studies served to evaluate coefficients necessary to determine evaporation reduction during periods of chemical application.

During the months of June through October of 1965, an evaporation study was conducted at Lake Hefner for the purpose of evaluating coefficients in the mass and heat transfer equations. This thesis reports the results of evaluating the mass transfer coefficient.

The study was a part of an overall research project on evaporation suppression. The principal investigating agencies in the study were the Agricultural Engineering Department of Oklahoma State University and the Water Conservation Branch of the United States Bureau of Reclamation. The Bureau planned and instrumented the project and Oklahoma State operated the experimental apparatus and acquired and analyzed the data.

Lake Description

Lake Hefner is located in Northwest Oklahoma City and represents one of the municipal water supplies for the city. The lake, shown in Figure 1, is an approximately circular-shaped reservoir formed by a 3 1/2 mile long horseshoe-shaped dam on Bluff Creek. It is situated on high ground being well exposed to the prevailing southerly wind.

Lake Hefner was selected for this study because of its physical characteristics and its reasonably accurate water budget control. Inflow consists mainly of flow from a diversion canal from the North Canadian River. Precipitation averages 31 inches in the area. A dike has been constructed on the south side of the lake which prevents most precipitation runoff from entering the lake. Therefore, runoff from the 1000 acre watershed is small compared to

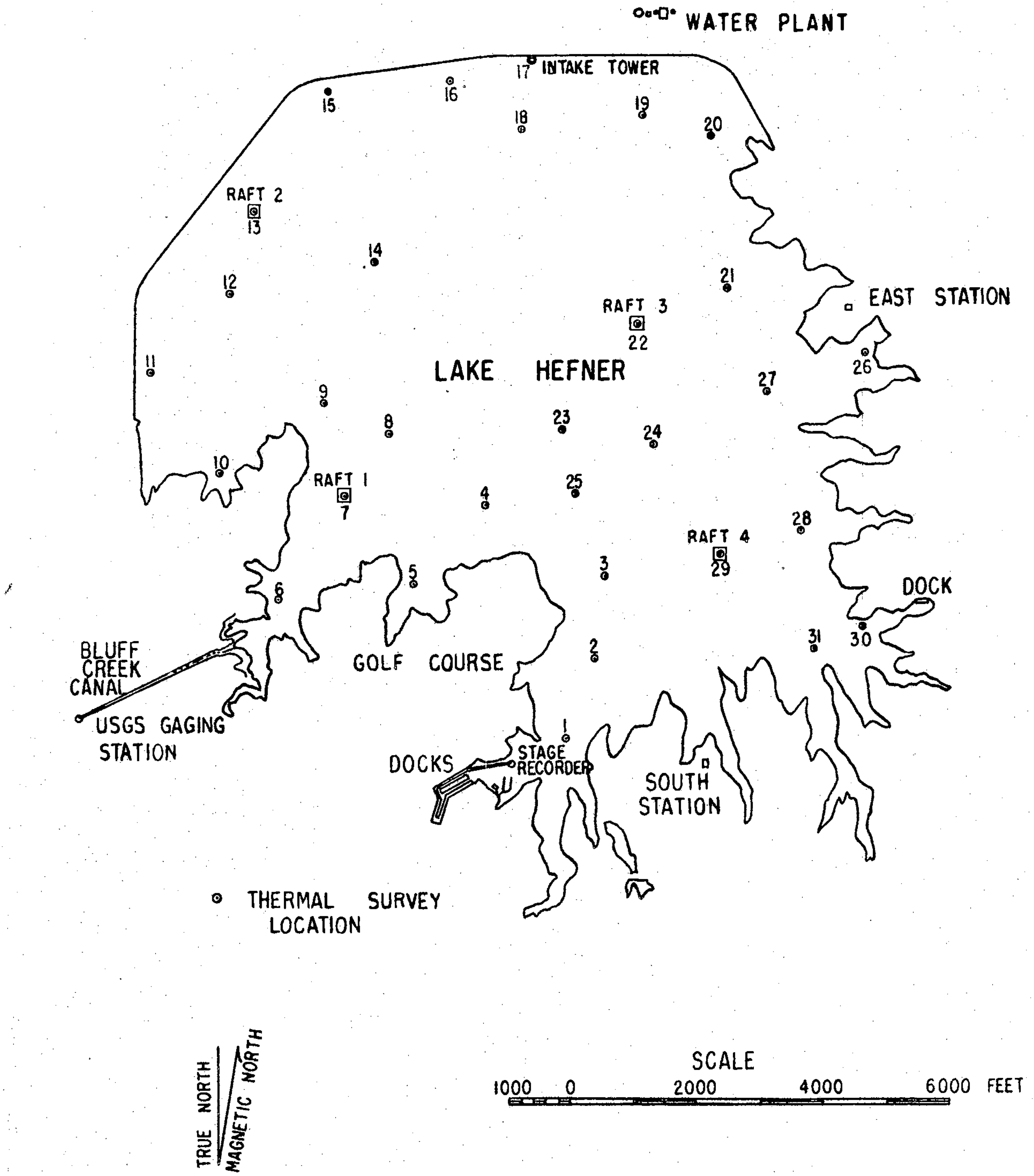

Figure 1. Map of Lake Hefner Showing the Instrumentation Stations and the Location of the Thermal Survey Points for the 1965 Investigation.

inflow through the diversion canal. Outflow is represented by seepage losses and golf course and water plant withdrawals.

CHAPTER II

OBJECTIVES

The three objectives set for this thesis were:

1. Determine the evaporation from the reservoir by energy budget and water budget methods.
2. Determine the coefficient, N, for the mass transfer equation, from both water budget and energy budget evaporation evaluations.
3. Determine the "best fit" equation that describes the seasonal variation of the mass transfer coefficient N.

CHAPTER III

REVIEW OF LITERATURE

Mass Transfer

Dalton (1798) first described the fundamental force effecting evaporation, that due to vapor pressure differences over the evaporating surface. After conducting experiments to define the factors that influence the functional relation between evaporation and the vapor pressure difference , he summarized his results only in a statement which has been expressed in equation form by later investigators as

$$E = C(e_s - e_d)$$

where E = evaporation, in./day

C = coefficient whose value depends upon barometric pressure, wind velocity, and other variables

e_s = vapor pressure of the air at the water surface evaluated at the water surface temperature, in. Hg

e_d = vapor pressure of saturated air at the temperature of the dew point, in. Hg

Fitzgerald (1886) conducted extensive experiments both under controlled and uncontrolled conditions studying effects of wind, atmospheric pressure, shading from sun, and depth. Possibly the first photographs of an evaporation experimental setup were presented. Fitzgerald's equation was

$$E = (0.40 + 0.199\ W)\ (e_s - e_d)$$

where W is the mean velocity of the wind in miles per hour.

A very complete series of evaporation experiments were conducted by Bigelow (1907-10) for the U.S. Weather Bureau. He formulated the equation

$$E = 0.138\ \frac{e_s}{e_d}\ \frac{d_e}{d_s}\ (1 + 0.07\ W)$$

where E = evaporation, cm/24 hr

e_s and e_d = vapor pressures, mm

W = wind velocity, Km/hr

$\frac{d_e}{d_s}$ = rate of change in the maximum vapor pressure with temperature

Rohwer (1931) working in Colorado conducted extensive investigations under controlled and uncontrolled conditions investigating wind and altitude effects on evaporation. With controlled wind conditions, he was able to formulate the equation

$$E = (0.44 + 0.118\ W)\ (e_s - e_d)$$

which compares with Carpenter's (1887) modification of

Fitzgerald's equation for western conditions. The modified equation was

$$E = (0.39 + 0.187\ W)\ (e_s - e_d)$$

For large lakes and reservoirs Rohwer proposed the equation

$$E = 0.771\ (1.465 - 0.0186\ B)\ (0.44 + 0.118\ W)(e_s - e_d)$$

for use between the altitude range of 68 feet below sea level to 14,109 feet above sea level. The quantity (1.465 - 0.0186 B) was a correction factor for altitude with B defined as the mean barometer reading in inches of mercury at 32 degrees Fahrenheit.

Investigators following Rohwer attempted to evaluate the coefficient to the vapor pressure deficit on a more theoretical basis. Anderson, Anderson, and Marciano (1950) reviewed the efforts of those investigators in a survey of evaporation theory and instrumentation. They selected eleven evaporation equations to be tested in the 1950-51 Lake Hefner studies. Marciano and Harbeck (1954) reported that Sverdrup's 1937 equation and Sutton's 1949 equation both gave results in good agreement with the results of the water budget at Lake Hefner. It was also concluded that the Thornwaite-Holzman equation would give satisfactory results if suitable instrumentation were available.

Several empirical equations for evaporation were formulated as a result of the Lake Hefner study. A "best fit" equation for the Lake Hefner data was

$$E = 6.25 \times 10^{-4} \; U_8 \, (e_o - e_8) \qquad (1)$$

where E = evaporation rate, cm/3 hr.

U_8 = wind speed at 8-meter height, knots

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

e_8 = vapor pressure of the air at the 8-meter level, mb

Another equation

$$E = 6.47 \times 10^{-4} \; U \, (e_o - e_a) \qquad (2)$$

which agreed well with the "best fit" equation was presented as the result of a study of Weather Bureau data from Will Rogers Airport, located 13 miles south of Lake Hefner. Other equations derived from the Lake Hefner study were presented by Linsley, Kohler, and Paulhus (1958). The equations were

$$E = 0.00304 \, (e_s - e_2) \, V_4 \qquad (3)$$

(e_2 and V_4 over lake)

$$E = 0.00270 \, (e_s - e_2) \, V_4 \qquad (4)$$

(e_2 over lake and V_4 upwind)

where E is the lake evaporation in inches per day, vapor pressure, e, is in inches of mercury, wind velocity, V, is in miles per day, and numerical subscripts designate height above surface in meters.

Harbeck and Kohler (1958) reported the Lake Hefner "best fit" equation gave satisfactory results at Lake Mead on a yearly basis. The 1949 Sutton equation and a modification of the 1937 Sverdrup equation were found to be unsuitable for determining evaporation at Lake Mead. Equation 3 presented by Linsley, Kohler, and Paulhus was reported to have yielded excellent results.

Subsequent versions of Lake Hefner empirical equations were used at Lake Hefner in 1958, Sahuaro Lake in 1960, Lake Cachuma in 1961, and Pactola Reservoir in 1962 and 1963 during evaporation suppression investigations at those sites. A 1963 and 1964 evaporation study at Elephant Butte Reservoir also utilized a form of the equation. The general form used to express the equation at all locations was

$$E = Nu\,(e_o - e_a) \tag{5}$$

where N is the mass transfer coefficient.

Energy Budget Method

When Dalton first studied evaporation he recognized the energy balance method as an approach to determine evaporation. Schmidt (1915) applied the energy budget to compute evaporation from oceans on an annual basis whereby he was able to neglect the change in storage energy over the study interval. Evaporation from a lake in Sweden was computed by Ångström (1920) using energy balance methods. Bowen (1926) took Cummings (1925) statement of the relation between evaporation and radiant energy over any time interval and formulated the analogous equation

$$I = S + LE + K$$

where I = solar and sky radiation corrected for reflection, minus the back radiation

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

LE = the product of the latent heat of vaporization, L, and the mass evaporation, E

K = small correction to cover other losses

The losses referred to were due to conduction and convection which were put equal to R times the losses by evaporation. The equation with K replaced by R (LE) was

$$I = S + LE (1 + R)$$

where R is Bowen's Ratio which describes the relationship of energy going into sensible heat to the energy going into evaporation.

An experiment using a well insulated pan and two tanks was conducted by Cummings and Richardson (1927). Using energy budget concepts on both the pan and tanks it was concluded that pan evaporation could be used to compute lake evaporation from the energy equation

$$E = (H-S-C)/L(1 + R)$$

where E = evaporation

H = difference in incoming and outgoing radiation determined from pan evaporation

C = correction for heat carried by flowing water and leakage of heat through the walls of the pan

It was also concluded that if the back-radiation to the sky could be measured with "satisfactory precision and convenience" that the pan would not be needed. Richardson (1931) studied the effects of insolation on evaporation using energy concepts. The energy budget equation which Cummings and Richardson had given checked experimentally with observed evaporation in California and also gave satisfactory results when applied to bodies of water outside California. Back-radiation from the water surface was computed by the Stefan-Boltzman relation. The sensible heat and conduction during the evaporation intervals were determined to be negligible.

Sverdrup (1940) applied the energy budget to the Bay of Biscay assuming that the advected energy was negligible due to the absence of distinct currents. He also investigated the Japanese Kuroshi current where it was assumed that the advected energy was constant throughout the year. He then determined the advected energy from the energy budget by first assuming that evaporation was negligible during early summer. Holzman (1941) admitted that the heat-balance method for determining evaporation from water-bodies was theoretically precise but stated that the difficulties that would be encountered in accurately measuring the pertinent parameters in the equation would invalidate the practical usefulness of the technique.

The evaporation at Lake Hefner in 1950 and 1951 was computed from the energy budget concept. Anderson (1954) reported that a correction to the energy budget equation was needed for advected energy loss due to the evaporated water. It was also concluded that for time intervals in the order of 7 to 10 days, the accuracy of the energy budget was probably adequate for evaporation determinations from lakes. Subsequent evaporation and evaporation suppression investigations including Lake Mead and other lakes throughout the West have used the energy budget as a control, its accuracy and usefulness having been demonstrated by the Lake Hefner study.

CHAPTER IV

THEORY

Water Budget Method

A direct approach to the problem of determining evaporation from a body of water is that of maintaining a water budget. The water budget is based on the Law of Conservation of Mass as applied to an open system where flow crosses the boundary of the system. Therefore, the mass flow entering the water body minus the mass flow leaving is equal to the change in mass storage. The relationship can be expressed by the continuity equation for a single one phase substance. With all quantities evaluated over the same time interval the expression is

$$M_2 - M_1 = M_I - M_0$$

where M_1 = initial mass storage

M_2 = terminal mass storage

M_I = mass inflow

M_0 = mass outflow

If $M_I = m_p + m_i$ and $M_0 = m_o + m_g + m_e + m_b$ then the equation may be written as

$$M_2 - M_1 = m_p + m_i - m_o - m_g - m_e - m_b$$

or by its equivalent in terms of volume and density

$$\rho_2 V_2 - \rho_1 V_1 = \rho_p v_p + \rho_i v_i - \rho_o v_o - \rho_g v_g - \rho_e v_e - \rho_b v_b$$

where $\rho_p v_p$ = precipitation mass inflow

$\rho_i v_i$ = surface mass inflow

$\rho_o v_o$ = surface mass outflow

$\rho_g v_g$ = seepage mass outflow

$\rho_e v_e$ = evaporation mass outflow

$\rho_b v_b$ = bank storage outflow

By assuming density equal and constant for all quantities and also assuming bank storage negligible over the time interval the equation may be rearranged and put into the familiar form

$$E = I + P - O - O_g - \Delta S \tag{6}$$

where E = volume of evaporated water

I = volume of surface inflow

P = volume of precipitation inflow

O = volume of surface outflow

O_g = volume of seepage outflow

ΔS = change in storage volume

Although surface inflow, precipitation, surface outflow and change in storage can be measured directly, measurements of seepage losses and any existing bank storage are difficult to measure. Therefore, estimates are used to determine these two quantities in most cases. Langbein, Hains, and Culler (1951) reported that both seepage and evaporation could be estimated by simultaneous solution of the water-budget and mass transfer equations. This would be accomplished by obtaining a stage seepage relation during periods of no evaporation as defined by the mass transfer equation.

Lake Hefner was first chosen as a study lake after a survey by Harbeck and others (1951) of more than 100 lakes and reservoirs in the West. The main reason Lake Hefner was chosen was because of its accurate water budget. It was reported by Harbeck and Kennon (1952) that daily evaporation results computed from the water budget were considered to be within 5 percent error one-third of the time and within 10 percent two-thirds of the time.

Mass Transfer Method

Evaporation as described by the theoretical mass transfer concept is a boundary layer phenomenon dependent upon the similarity of the coefficient of vapor transport to that of momentum transport. Assumptions of wind and height distribution in theoretical derivations of mass transfer equations have introduced a roughness parameter which has been very difficult to evaluate on a practical basis. There have been different theories presented on the thickness of the boundary layers over water surfaces. One investigator, Sverdrup, reported a two-layer equation in 1937 and a one-layer equation in 1946. Whether the atmospheric boundary layer is stable, neutral (adiabatic), or unstable has necessitated assumptions on the part of the investigators. Without exception, the equations resulting from theoretical derivations have been complex mathematical expressions. Practical measurement of the pertinent quantities demands extensive meteorological instrumentation. In addition the tested equations have not given reliable results at all locations.

For this study the semi-empirical equation

$$E = N\, u_2\, (e_o - e_a)$$

was used where

E = evaporation rate, cm/day

u_2 = average wind speed at a height of 2 meters above the water surface, Km/day

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

e_a = average vapor pressure of the air, mb

N = mass transfer coefficient, cm/Km-mb

The mass transfer coefficient, N, determined at previous evaporation investigations appeared to have a seasonal variation. It has been proposed that the seasonal variation of N for the study interval at Lake Hefner may be described by an equation.

Energy Budget Method

The energy-budget concept of evaluating evaporation from a body of water is ultimately based on the Law of Conservation of Energy. All energy entering the body minus the energy leaving the body equals the change in storage energy. The energy, in calories, can be expressed in equation form for some time period as

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_o \tag{7}$$

where Q_s = incoming short-wave or solar radiation

Q_r = reflected short-wave radiation

Q_a = incoming long-wave or atmospheric radiation

Q_{ar} = reflected long-wave radiation

Q_{bs} = back-radiation emitted from water surface according to Stefan-Boltzmann Law for a gray body

Q_v = net advected energy into the body of water

Q_e = energy necessary for phase change from liquid to vapor with negligible change in temperature (latent heat of vaporization)

Q_h = energy transfer from the body of water to the atmosphere or sensible heat

Q_w = energy advected to the atmosphere with the evaporated water

Q_o = change in thermal energy storage of the water body

Transformation of kinetic energy to heat, heating due to chemical or biological processes, and conduction of heat through the bottom are considered negligible.

In order to determine evaporation two more relationships are needed. Bowen's ratio, R, is the ratio of the sensible heat, Q_h, to the energy of evaporation, Q_e, expressed as

$$R = \frac{Q_h}{Q_e} \text{ and } Q_h = RQ_e = R\rho LE$$

where ρ = mass density of the evaporated water, g/cm^3

E = volume of evaporated water, cm^3

L = latent heat of vaporization, cal/g

The energy, Q_w, advected with the evaporated water mass, is expressed as

$$Q_w = \rho C_p E(T_o - T_b) \tag{8}$$

where C_p = constant pressure specific heat of the evaporated water, cal/g-°C

T_o = water surface temperature or evaporated water temperature, °C

T_b = arbitrary base temperature taken as 0°C

Making the substitutions for Q_e, Q_h, and Q_w, and rearranging the terms the expression for the volume of evaporated water, E, becomes

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_o}{\rho[L(1+R) + C_p(T_o - T_b)]} \tag{9}$$

Previous studies at Lake Hefner indicate that the evaporation may be estimated by the energy budget with deviation of ± 5 percent from the mean energy budget evaporation. To achieve this precision all individual parameters, especially the change in energy storage, must be evaluated with the highest possible precision.

Solar Radiation - Q_s

The short-wave radiation impinging on the water surface is partly radiation direct from the sun and partly that radiation reflected or scattered. Wavelengths of approximately 0.17 micron to 4 microns according to Brunt (1939) with maximum number at 0.49 micron are emitted by the sun's surface radiating as a black body at approximately 6000 degrees Kelvin. The incoming radiation incident on a horizontal surface depends on the altitude of the sun, atmospheric absorption, and the type and amount of cloudiness. Ozone in the atmosphere absorbs all those wavelengths below 0.3 micron. The sun's radiation in passing through the atmosphere is subjected to absorption by gaseous constituents and water vapor, reflection at cloud surfaces and water drop surfaces, and scattering by the suspended particles in the atmosphere. Only about half of the incident radiation at the atmosphere's outer limit becomes available for heating the earth's atmosphere and surface.

Computations of the solar radiation flux have been made with empirical equations but direct measurements give the greatest accuracy.

Reflected Solar Radiation - Q_r

Part of the solar radiation is reflected diffusely by the water surface. Powell and Clarke (1936) stated that solar radiation was diffusely reflected partly by the water surface and partly by a layer of opaque water just beneath the surface. Results of the 1951 Lake Hefner observations support that conclusion. The amount reflected is dependent upon sun altitude, atmospheric turbidity, and the water surface roughness. Beard and Wiebelt (1965) assumed a sine wave configuration for the water wave and determined theoretical values for reflectance as a function of the water wave amplitude to water wavelength ratio and also as a function of the angle of incidence. It was reported that for diffuse irradiation, water waves could decrease the theoretical reflectance by nearly 50 percent. Koberg (1964) presented a fast and uncomplicated indirect method of determining reflected solar radiation from a water surface. The solar radiation that would have been received for the period had no clouds been present (clear sky radiation) was obtained from the solar radiation chart in Figure 2. Using the family of curves shown in Figure 3 which were developed by Koberg, the reflected energy was

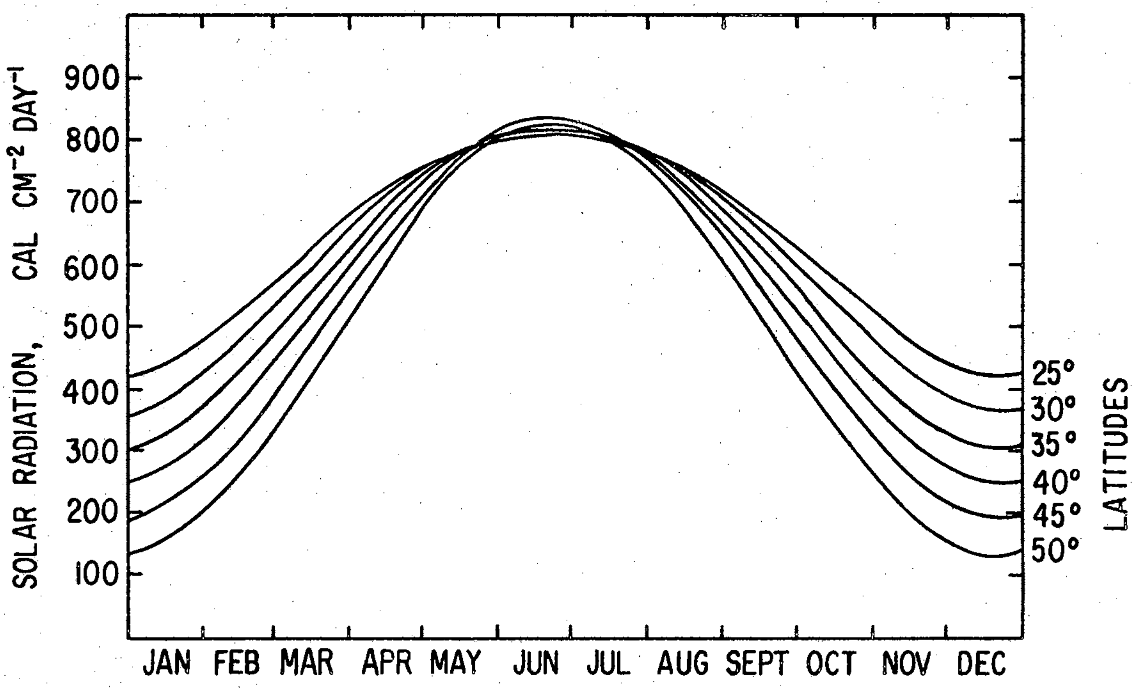

Figure 2. Clear-Sky Solar-Radiation at Latitudes Between 25° and 50° for All Months.

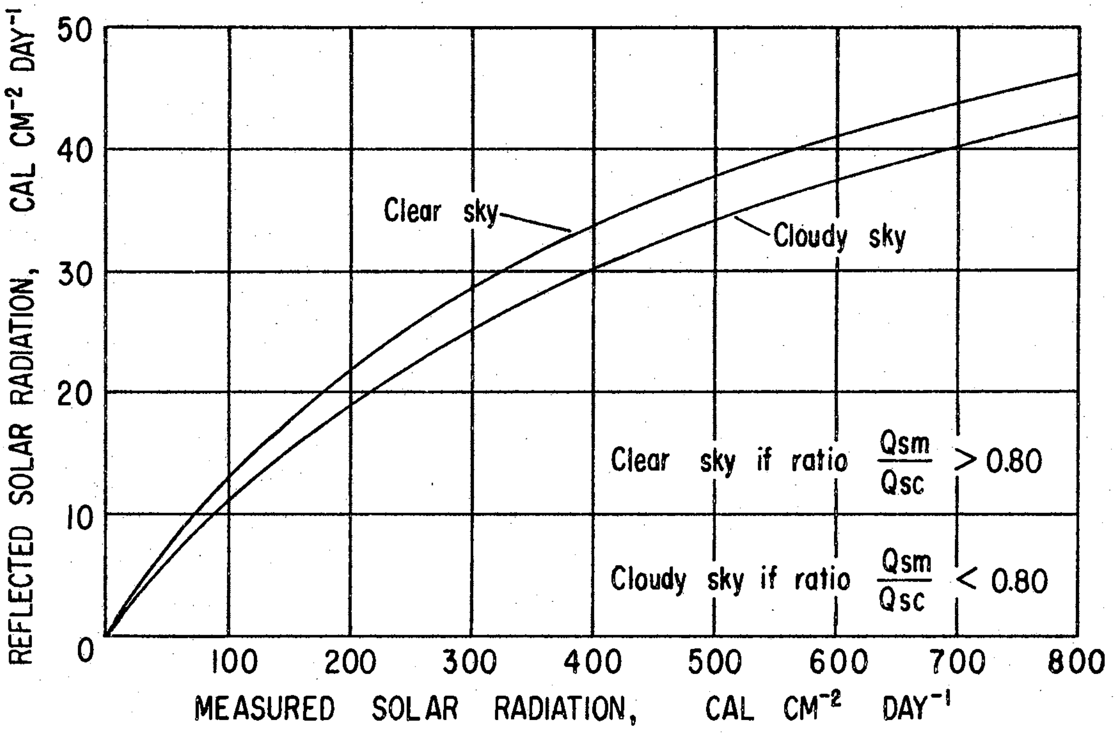

Figure 3. A Relationship to Determine Reflected Solar Radiation from Measured Solar Radiation for Clear and Cloudy Skies.

determined by classifying the period either cloudy or clear and then entering the graph to the correct curve with the measured radiation. A clear sky was defined as one in which the ratio of the measured radiation to the clear sky radiation was greater than 0.8 and a cloudy sky would be one with a ratio less than 0.8.

Atmospheric Radiation - Q_a

Long-wave radiation from the atmosphere comes almost wholly from the energy emission of the water-vapor in the atmosphere. The vapor radiates as a black body at stratospheric temperatures of about 200 degrees Kelvin in wavelengths between 4 microns and 120 microns.

Reflected Atmospheric Radiation - Q_{ar}

Reflectivity of atmospheric radiation by a water surface has been determined by the Physical Standards Laboratory, Institute of Engineering Research, University of California. After a test on water samples including one Lake Hefner sample, the value as given in the 1952 Lake Hefner report was 0.030 ± 0.005 over a range of water temperatures from 0 to 30 degrees Centigrade.

Back Radiation from Water Surface - Q_{bs}

The long-wave radiation from a water surface is a function of the fourth power of the absolute temperature of the water surface. If the water surface radiated as a black body, the Stefan-Boltzmann relation would describe its energy emission. However, the water surface is known to radiate as a gray body which does not qualify as a perfect emitter as in the case of the black body. A gray body has nearly a constant emissivity over a certain range of wavelength. Monochromatic emissivity is defined as the ratio of the monochromatic emissive power of the gray or non-black body to that of a black body at the same temperature and wavelength of radiation. Gray body radiation would be computed by multiplying the black-body radiation by the average emissivity.

Emissivity for lake water surfaces has been determined by considering the water to be opaque to long-wave radiation making the reflectivity plus the absorption equal to unity. For thermal equilibrium from Kirchoff's Law, emissivity would equal absorptivity and the emissivity value would become equal to 0.970 ± 0.005 in the temperature range 0 to 30 degrees Centigrade.

Advected Energy - Q_v

The net advected energy to the reservoir is the net energy gain due to flow volumes entering and leaving the body of water. Advected volumes for Lake Hefner would be the result of surface inflow, municipal withdrawals, and rainfall. Advected energy due to seepage and golf course irrigation withdrawals were considered negligible for energy budget computations.

A base temperature must be used as a reference in the computations of internal energy carried by the volumes of water. All advected energy at Lake Hefner was referenced to 0 degrees Centigrade.

Stored Energy - Q_o

The stored energy term represents the net gain of stored thermal energy or internal energy of the reservoir over the thermal survey period. A thermal survey period is the time interval between temperature profile surveys of the water body. The profiles are taken at numerous points over the lake in an attempt to establish the instantaneous internal energy of the reservoir. The internal energy is referenced to some arbitrary base temperature usually chosen as 0 degrees Centigrade for convenience. A numerical integration method is used to calculate the energy stored in the body of water by layers. The expression for the initial energy stored, Q_1, would be

$$Q_1 = \sum_{i=1}^{n} \rho C_p (T_i - T_b) A_i \Delta h_i$$

where ρ is the mass density, C_p is the specific heat at constant pressure, T_i is the average temperature of the layer, A_i is the average area of the layer, and Δh_i is the layer thickness. If the terminal energy storage, Q_2, were expressed similarly, then the change in stored thermal energy, Q_o, over the period would be expressed as

$$Q_o=Q_2-Q_1=[\sum_{i=1}^{n}\rho C_p(T_i-T_b)A_i\Delta h_i]_2-[\sum_{i=1}^{n}\rho C_p(T_i-T_b)A_i\Delta h_i]_1$$

Prerequisites to obtaining adequate evaporation determinations are a reasonably accurate area-capacity table and thermal survey periods of seven days or longer for stored energy evaluation.

Bowen's Ratio - R

Bowen (1926) expressed the relationship between sensible heat and the latent heat used for evaporation at the water surface as the ratio

$$R = \beta\frac{(T_o-T_a)P}{(e_o-e_a)1000} \tag{10}$$

where T_o and T_a are the temperatures of the water surface and air in degrees centigrade, e_o and e_a are the saturated vapor pressure at the water surface temperature and the vapor pressure of the air, respectively, in millibars. P is the atmospheric pressure in millibars, and β is a coefficient usually taken as 0.61 under normal atmospheric conditions. The fundamental equations Bowen used to derive the relationship apply to molecular diffusion processes of heat and water vapor transfer. Consequently it could be concluded that the computed ratio would be valid only for laminar flow cases. However, Bowen stated that convection could be expected to affect heat losses by evaporation and diffusion and conduction in the same manner and implied the "ratio" would be independent of the state of atmospheric turbulence. Observations by Cummings and Richardson (1927) tended to support Bowen's theoretical conclusions respecting the "ratio". Again in 1940 Cummings made reference to the reasonableness of Bowen's ratio. Sverdrup stated in 1943 that the formula would give only an approximate value. Pasquill in 1949 found that the eddy diffusivities for water vapor and heat could only be identical under stable conditions and would vary independently in unstable conditions. Even with the doubts raised about the validity of Bowen's Ratio, it did allow a direct computation of evaporation when there were no direct solutions for either the sensible heat or the latent heat for the evaporation.

CHAPTER V

INSTRUMENTATION AND PROCEDURES

Measurement of the pertinent meteorological quantities needed in the energy and water budget methods for evaporation computation required one main instrument station, one back-up station and one auxillary station. The station locations are shown in Figure 1. The parameters needed were:

1. Incoming solar radiation
2. Total incoming radiation
3. Water surface elevation
4. Precipitation
5. Rate, duration, and temperature of inflow
6. Rate, duration, and temperature of outflow
7. Water surface temperature
8. Lake temperature profile
9. Relative humidity and air temperature

Determination of the mass transfer coefficient, N, required that the wind speed, u, also be measured.

The principal instrument station shown in Figure 4 was located on the south shore of the lake. Radiation instruments, anemometers, wind vane, hygrometers and a rain gage were located at the site. An air-conditioned trailer housed

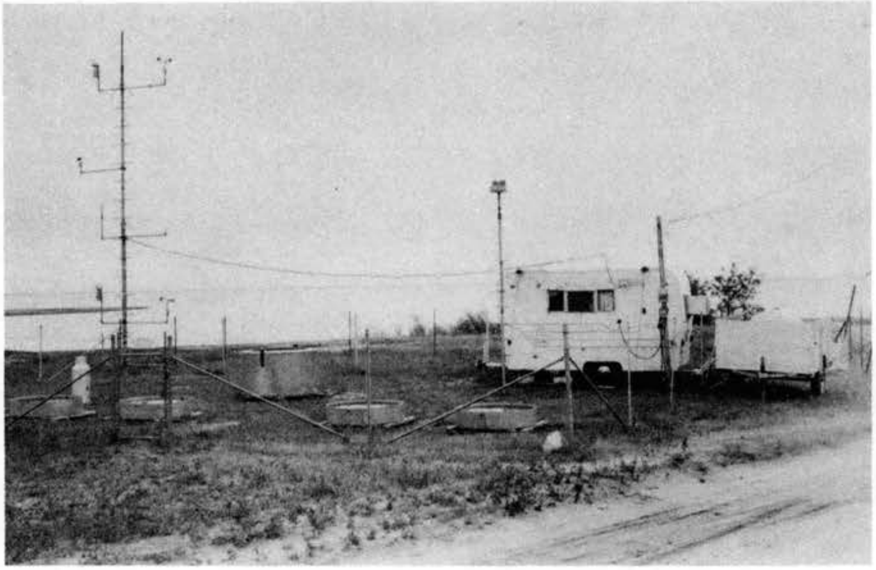

Figure 4. South Station Instrument Site.

Figure 5. Intake Tower Instrument Site.

the multipoint potentiometer recorders, constant power supply transformer, humidity indicator and standard time clock.

A complete set of back-up instruments was located at the intake tower on the north side of the lake. The tower is shown in Figure 5. The auxiliary station on the east shore was used as a rain gage site.

Each day a check was made at the instrument sites to check the outputs of the instruments. Maintenance and servicing were performed as needed. Meteorological instrumentation at the south station provided the data used in all computations except those when periods of missing data occurred.

Incoming Solar Radiation

Incoming sun and sky radiation, Q_s, from the whole hemisphere was detected by a 50 gold-palladium and platinum-rhodium alloy thermojunction Eppley pyrheliometer (pyranometer). The device, shown in Figure 6, was mounted 13 feet above the ground. The instrument consists of a thermopile mounted in good thermal contact under thin flat concentric silver ring receivers, but electrically insulated from them. The inner ring is coated black and the hot junctions are attached behind the ring. The cold junctions are attached to the white outer ring. A central ring is also white. According to the manufacturer the soda lime glass bulb enclosing the receiving assembly transmits radiation

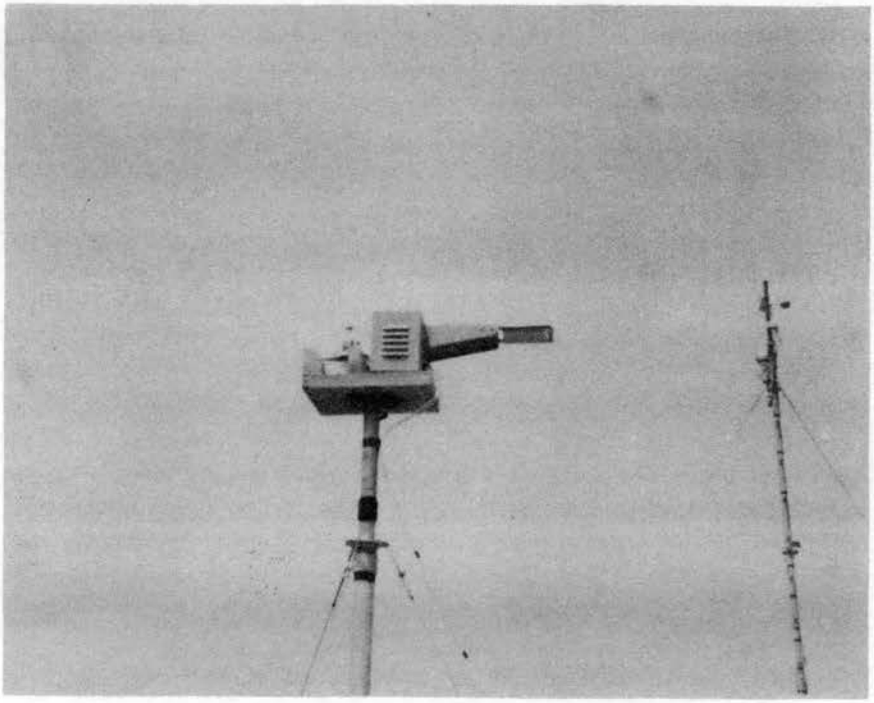

Figure 6. Eppley Pyrheliometer and Beckman-Whitley Flat Plate Radiometer Located at South Station.

wavelengths from approximately 0.28 micron to 5 micron. However, Gates (1962) stated that "any instrument which has a glass dome or cover is limited in its wavelength response to the range 2800 A to 30000 A" (0.28 micron to 3 microns). The thermopile in the receiving assembly senses the temperature difference between the hot black absorptive receiver and the cool white reflective receiver and transduces the difference to an analogous electrical signal. The output was modified by a voltage divider so that it was recorded by a Honeywell Universal Electronik recorder directly in radiation flux units of langleys per minute. A point value was recorded every minute and formed the trace shown in Figure 7. The glass bulb was wiped with a soft cloth weekly to remove dust and thereby maintain the sensitivity required.

Total Incoming Radiation

Atmospheric long-wave radiation, Q_a, was determined indirectly by subtracting the short-wave radiation as detected by the pyrheliometer from the total incoming radiation. Total incoming hemispherical radiation was detected by a Beckman and Whitley thermal radiometer mounted on the same mast as the pyreheliometer, as shown in Figure 6. The thermal radiometer sensing element acts as detector and transducer. The element is composed of silver-constantan thermopiles arranged in two thin phenolic resin plates sandwiched at the interfaces of three bakelite

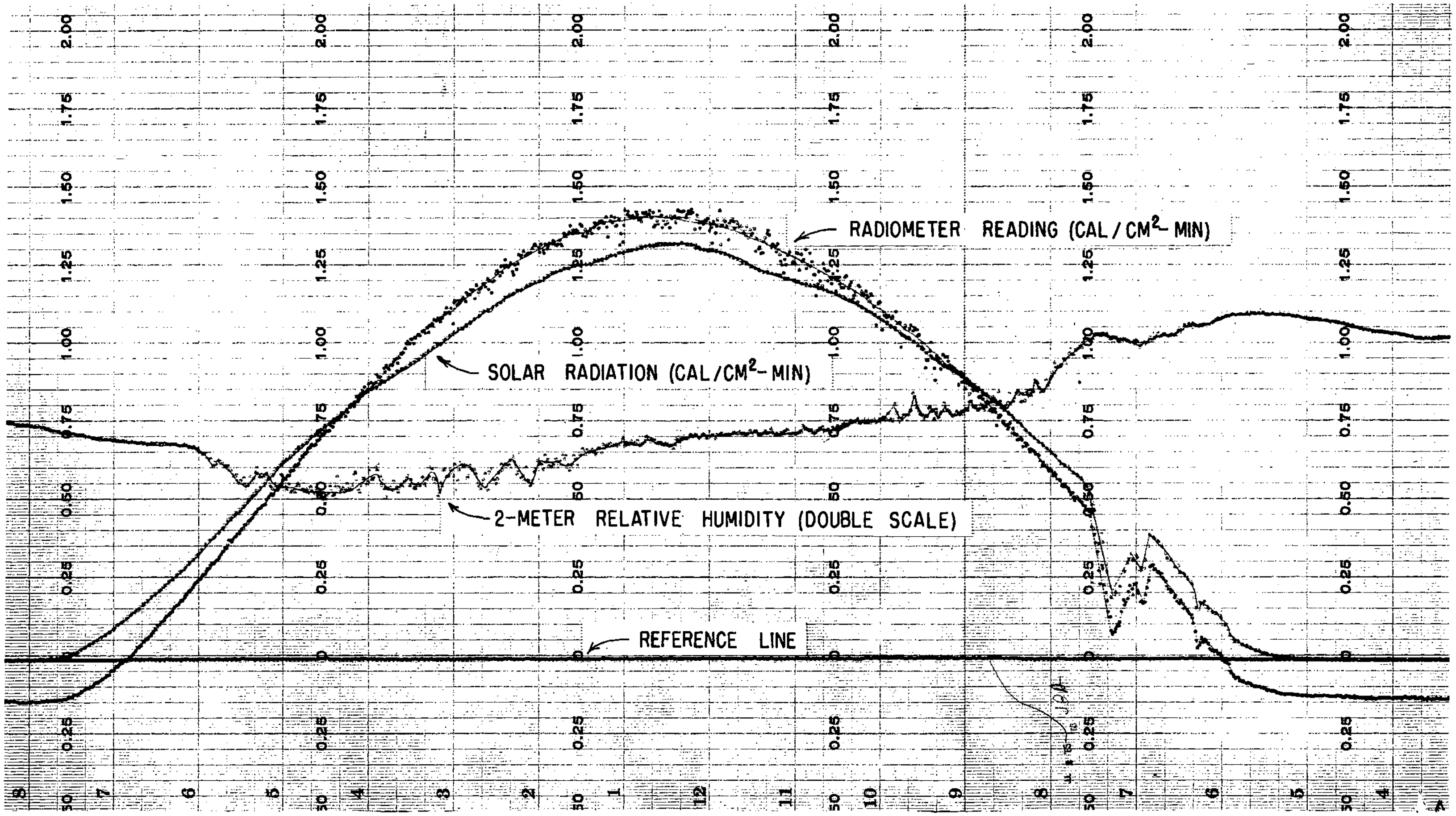

Figure 7. Minneapolis-Honeywell Recorder Traces of Output from Radiation and Relative Humidity Sensing Instruments at South Station.

plates. The upper bakelite plate is covered by aluminum sheet painted black to absorb all radiation non-selectively. The lower plate is covered by aluminum sheet polished to reflect all wavelength radiation. An aluminum plate is mounted a small distance below the plate. The temperature gradient between the "hot and cold junctions" induces heat flow and an electromotive force proportional to the heat flow. Convection effects of the wind were theoretically eliminated by maintaining equal convection on both sides of the element with a blower. The electromotive force is proportional to the incident minus the black-body radiation of the plate which has caused the temperature difference. Output of the instrument was recorded by the self-balancing multipoint recorder directly in langleys per minute by means of a voltage divider in the circuit. A trace of points recorded every minute is shown in Figure 7. The electromotive output from a thermocouple mounted in the black aluminum sheet was recorded on a second multipoint recorder for use in computing the back radiation of the black plate. The plate was washed each week to remove dust and maintain sensitivity.

Water Surface Elevation

Two Stevens Type A-35 recorders monitored the lake stage continuously. The instruments had 1:1 gage height ratios and a 9.6 inch per day time scale. The south lake gage was located at the small boat harbor on the northeast end of the north boat docks, about 50 feet from shore. A short line of levels was run from a U.S.G.S. datum to the boat dock gage which was set to sea level datum. The north lake stage recorder was installed on the intake tower on June 25. Approximate agreement between the two recorders was set on a very calm day, July 16, using the lake level as the datum. A final adjustment was made by comparing the traces during two exceptionally calm periods, 1100 July 30 and 1800 August 3, and the pen setting on the intake tower recorder graph was adjusted to agree with the boat dock recorder. The instruments were checked each day for time and trace inking.

Precipitation

Rainfall for energy budget calculations was measured by two Weather Bureau recording raingages at the south station and the east station and by a standard Weather Bureau non-recording raingage at the Intake Tower. An additional raingage at the filter plant shown in Figure 1 was used in the water budget computations. The raingages were checked each day. Precipitation amounts were measured volumetrically to check the chart reading.

Temperature of the rainfall was taken as the average of the minimum temperature of the thermal radiometer black plate, observed during the rain, and the average wet bulb temperature as determined indirectly from relative humidity and dry bulb air temperature.

Rate, Duration and Temperature of Surface Inflow

Surface inflow was measured at the U.S. Geological Survey gaging station on the supply canal shown in Figures 1 and 8. This station consisted of a steel weir for low flows, a concrete weir for normal flows, and two Stevens A-35 stage recorders. The upper recorder measured head near the weir while the lower recorder measured head well down the canal near the outlet. Temperature of the flow volume was sensed by a mercury-in-steel pressure type probe connected by capillary to a Minneapolis Honeywell temperature recorder. The instrument had an accuracy of ± 5 percent and was checked each day with a mercury-in-glass thermometer.

Rate, Duration, and Temperature of Outflow

Withdrawals by the water plant were measured by Oklahoma City Water Department personnel using a venturi meter which flowed at approximately one-third its maximum rated capacity. The venturi meter accuracy is estimated to be within ± 3 percent of the true discharge rate. As a check, the amount of treated water pumped to the city mains was determined by the amount of electric energy used during

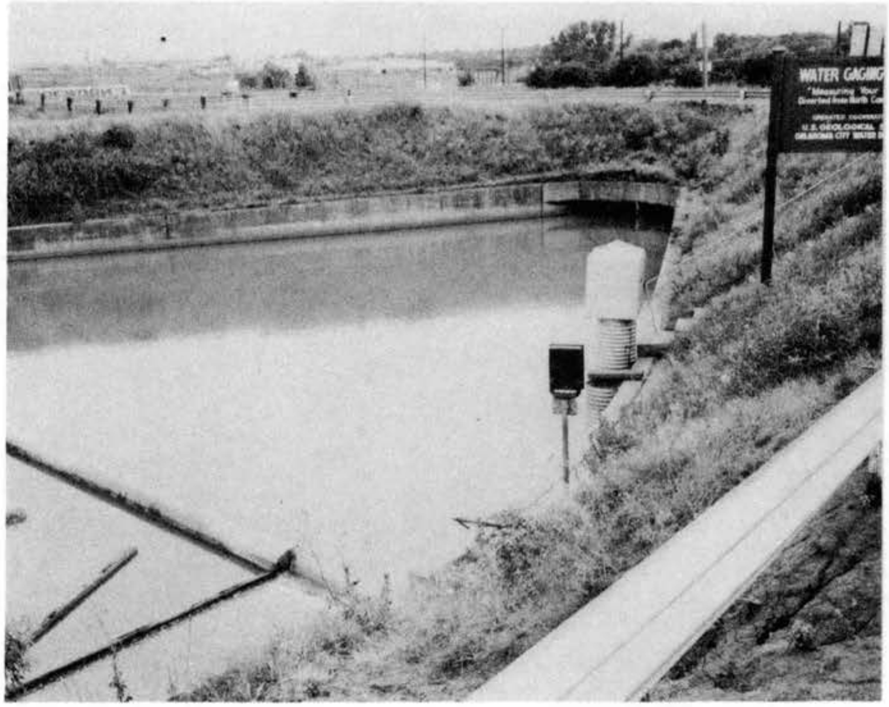

Figure 8. U.S. Geological Survey Gaging Station on the Lake Hefner Supply Canal.

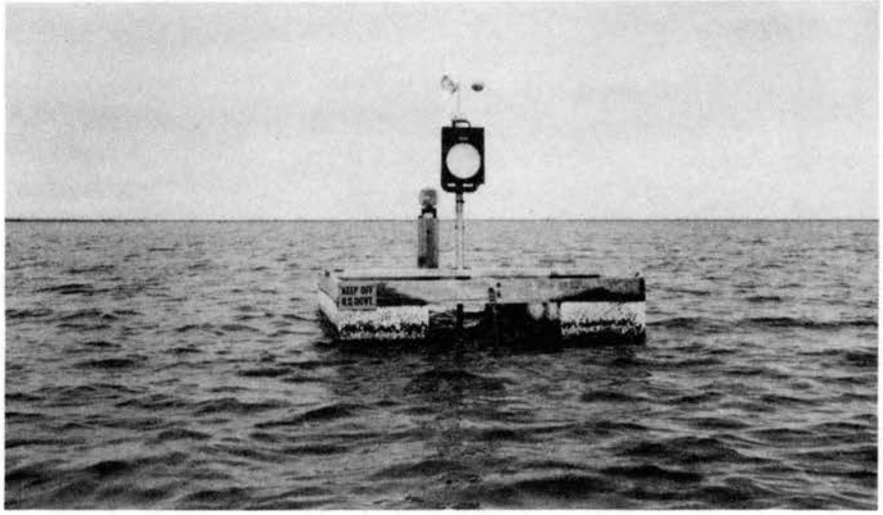

Figure 9. Typical Instrument Raft Measuring Wind Travel and Water Surface Temperature.

the pumping interval. After the wasted raw water had been considered, the adjusted value was in good agreement with the venturi amount. The raw water temperature was determined from a tap sample by water plant personnel each morning at 0830.

Shallow seepage losses were measured by six weirs located below the dam. The records on the seepage were maintained by the Oklahoma City Water Department.

Golf course irrigation withdrawals were determined from pump performance curves and pump running time as recorded by automatic timers on the four pumps. Readings were taken each day after the timers had been installed on August 19.

Water Surface Temperature

The water surface temperature, T_o, was recorded by recorders mounted on timber and styrofoam rafts located at four representative points in the lake as shown in Figure 1. The recorders were identical to the one at the inflow station. Depth of the probe was set at 1/2 inch below the lake surface. The rafts were visited every day when weather conditions would permit to check time and temperature on the recorders. Figure 9 shows a typical raft and recorder.

Wind action created large waves on the lake causing the probe to emerge from the surface and then submerge to depths of 2 or more inches. Though no instrument was available to check, it was assumed that there was no thermal gradient near the surface due to the constant wind action common to Lake Hefner. Excessive wave action during high winds caused the pens to fluctuate at times, forming thick lines of the temperature traces. Raft 3 was out of service much of the summer due to faulty capillary pen inking after having been installed late due to rough lake conditions.

Lake Temperature Profile

The internal energy of the reservoir body was obtained by making a thermal survey which consisted of temperature profiles at each of the thirty-one locations shown in Figure 1. Temperatures were measured at the surface and at depths of 2 1/2, 5, 7 1/2, and every 5 feet thereafter until the bottom was reached. A thermal survey period (TSP) consisted of the time interval between two thermal surveys, usually one week.

The temperature profile measurements were made with a Whitney Underwater Thermometer. This instrument has as its detector a housed thermistor bead at the end of a graduated electrical cable which is lowered from a boat. A change in temperature changes the resistance of the thermistor and thereby the current flowing through the circuit. A milliammeter is used to obtain a temperature reading to be corrected by a calibration curve for the 5 degree Centigrade temperature range that applies. Spot checks of the temperature readings with a mercury-in-glass thermometer were made during thermal surveys.

Relative Humidity and Air Temperature

The relative humidity and air temperature were needed to determine the vapor pressure of the air. Relative humidity was measured by two different type hygrometers during the study. Both hygrometers were made by Hygrodynamics, Inc. and operate on the same principle. The hygrometers were both mounted 2 meters above the ground.

Between June 3 and July 22 a non-direct-reading element was used which required ambient air temperature and calibration curve corrections. After July 22 a direct reading element was used which determined relative humidity directly in percent. Both elements consist of a number of sensing cells which are accurate within a specific range of relative humidity. The cell coating experiences a change in resistance proportional to the humidity change. The output voltage, which varied with the resistance, was recorded on a self-balancing multi-point recorder as double the percent relative humidity. A voltage divider was used to lower the voltage signal to the recorder. A typical humidity trace is shown in Figure 7.

Temperature of the air, T_a, blown through the hygrometers was sensed by a thermocouple. The voltage output was recorded on a second multipoint recorder in degrees Fahrenheit. The air temperature was used to make ambient temperature corrections on the solar radiation data and the non-direct-reading hygrometer data.

Wind Speed

Wind travel was recorded at the rafts in the lake by totalizing odometers mounted 2 meters above the water surface. The odometers were read each day during the raft check. Wind travel for 2-meter and 4-meter heights above the ground at the south station were registered by totalizing odometers and recorded on an Esterline-Angus ten point recorder. Wind directions were recorded on the same recorder by the eight points of the compass. Totalizing odometers also recorded wind travel at the 8-meter height. The odometers were read each day and the multichannel recorder was checked for trace inking and time.

CHAPTER VI

ANALYSIS OF DATA

Strip chart data traces were integrated by an Amsler Integrator capable of giving the area and the first and second moments of any closed plane figure. Glover (1961) presented a method of accounting for the functional variation of the recorded quantity by replacing the function, over the range of interest, by a Taylor series expansion and evaluating the series with the integrator values. This method was valuable in determining back radiation from the radiometer black plate. It was convenient to trace above a baseline other than zero radiation or zero temperature. Therefore, the integration constants for temperature were determined as shown in Appendix A. The baseline radiation is only a function of time interval of integration, and for this thesis was 0.5 calories per square centimeter per minute. Amsler integrator procedures such as these were also used in the Pactola Reservoir and Elephant Butte Reservoir studies.

The data were processed by thermal survey periods using desk calculators and an IBM 7040 computer. Table I shows the starting and ending dates and the time interval

TABLE I

THERMAL SURVEY PERIOD DATES AND TIME INTERVALS FOR THE 1965 LAKE HEFNER INVESTIGATION

TSP	BEGINNING		ENDING		TIME INTERVAL	
	Date	Time	Date	Time	Hrs.	Days
1	June 3	1230	June 10	0800	163.50	6.8125
2	June 10	0800	June 17	0800	168.00	7.0000
3	June 17	0800	June 24	0800	168.00	7.0000
4	June 24	0800	July 1	0830	168.50	7.0208
5	July 1	0830	July 8	0830	168.00	7.0000
6	July 8	0830	July 15	0830	168.00	7.0000
7	July 15	0830	July 22	0830	168.00	7.0000
8	July 22	0830	July 29	0800	167.50	6.9792
9	July 29	0800	Aug. 5	0830	168.50	7.0208
10	Aug. 9	1030	Aug. 16	1000	167.50	6.9792
11	Aug. 16	1000	Aug. 23	0700	165.00	6.8750
12	Aug. 23	0700	Aug. 31	0700	192.00	8.0000
13	Sept. 1	0800	Sept. 6	0730	119.50	4.9792
14	Sept. 6	0730	Sept. 10	0700	95.50	3.9792
15	Sept. 10	0700	Sept. 16	1200	149.00	6.2083
16	Sept. 24	1300	Oct. 2	0900	188.00	7.8333
17	Oct. 2	0900	Oct. 10	0730	190.50	7.9375
18	Oct. 10	0730	Oct. 23	0900	313.50	13.0625

for each period. Time intervals during which large rains caused runoff to flow over an ungaged weir on the south side of the lake were excluded from analysis because of the resulting inaccuracies in the water budget.

During the last part of thermal survey period (TSP) thirteen and during all of thermal survey period (TSP) fourteen, a hexadecanol and octadecanol compound was applied to the lake to suppress evaporation. The chemical was mixed with water to form a slurry which was injected into a main pipeline at the batch plant on the north side of the boat docks. The flow was then distributed into three header lines that lay on the lake floor near the south shore areas. Subsequently the flow rose through riser tubes and was sprayed onto the lake surface by rotating sprinklers. Film coverage of the lake was mapped by the plane table and alidade from the fifteenth floor of United Founder's Tower located approximately 2 miles southeast of the southeast shore of the lake. No attempt was made to determine evaporation reduction, if any, for the periods of application.

Solar Radiation

The area between the baseline and the solar radiation trace was determined with the Amsler Integrator. The area was converted to energy flux by the relationship that one square inch is equivalent to 16.338 calories per square centimeter. The base energy flux was added to the flux above the baseline. A slight drift of the recorder from the zero reference line made it necessary to apply a drift correction to the flux for the interval. An ambient temperature correction was applied and the energy flux was summed over the integrated intervals to obtain the total flux for the thermal survey period. Table B-1 shows the solar energy flux determination for TSP 8. The flux was multiplied by the average lake surface area to obtain the solar incoming energy, Q_s, for the thermal survey period. The calculated energy for TSP 8 was

$$\begin{aligned} Q_s &= (3566.75 \text{ cal/cm}^2)\ (1.01707 \times 10^{11} \text{cm}^2) \\ &= 3.62763 \times 10^{14} \text{ cal} \end{aligned}$$

Atmospheric Radiation

The strip charts recorded only a portion of the total radiation incoming to the flate plate, the other part of the radiation being back radiated to the atmosphere. The charts were analyzed with the Amsler Integrator in the same manner as the solar radiation except for the ambient temperature correction. This correction was needed due to the difference between the transducer temperature and the transducer calibration temperature. Table B-II shows the calculation for TSP 8.

The back radiation from the radiometer black plate was determined from the area and moments of the area under the plate temperature trace using the Amsler Integrator constants shown in Appendix A. These calculations are shown in Table B-III.

Total incoming radiation is the sum of the back radiation component and the recorded component. Atmospheric radiation was determined by subtracting the solar radiation from the total radiation. The incoming energy, Q_a, due to atmospheric radiation was then determined by multiplying the energy flux by the average water surface area for the thermal survey period. The calculated energy for TSP 8 was

$$\begin{aligned} Q_a &= [(2934.14 + 6976.52)\ \text{cal/cm}^2 - (3566.75) \\ &\quad \text{cal/cm}^2]\ [1.01707 \times 10^{11}\ \text{cm}^2] \\ &= 6.45220 \times 10^{14}\ \text{cal} \end{aligned}$$

Reflected Solar Radiation

Koberg's method was used to obtain the reflected solar radiation. The clear sky solar radiation was obtained from Figure 2 for the time of year and the Lake Hefner latitude, 35 degrees and 34 minutes. The ratio of measured solar radiation to clear sky radiation was the determining factor as to whether the thermal survey period was clear or cloudy. Figure 3 was used to obtain the reflected radiation. For TSP 8 the measured solar radiation was 511.1 calories per square centimeter per day and the clear sky radiation from Figure 2 was 785 calories per square centimeter per day. The ratio of the two values was 0.633. The ratio was less than 0.8, therefore TSP 8 was classified cloudy. The reflected solar radiation from Figure 3 was 34.6 calories per square centimeter per day. The reflected solar energy, Q_r, for TSP 8 was

$$Q_r = (34.6 \text{ cal/cm}^2\text{-day})\ (1.01707 \times 10^{11} \text{cm}^2)\ (6.9792 \text{ days}) = 0.24560 \times 10^{14} \text{ cal}$$

Table II shows the determination of reflected solar radiation by thermal survey periods.

Reflected Atmospheric Radiation

Reflected atmospheric radiation was assumed to be 3 percent of the incoming atmospheric radiation. For TSP 8 the atmospheric radiation energy was 6.45220×10^{14} calories. Reflected energy, Q_{ar}, was calculated as

$$Q_{ar} = (0.03)\ (6.45220 \times 10^{14}) = 0.193566 \times 10^{14} \text{ cal}$$

Water Surface Back Radiation

The lake surface temperature was recorded on a circular chart in degrees Fahrenheit. Hourly temperatures were obtained from the charts and an average value for the day

TABLE II

REFLECTED SOLAR RADIATION CALCULATION BY THERMAL SURVEY PERIODS

	Measured Solar Radiation	Clear Sky Radiation	Radiation Ratio	Conclusion	Reflected Solar Radiation	Reflectivity
TSP	Q_s	Q_{sc}	Q_s/Q_{sc}		Q_r	Q_r/Q_s
	cal/cm^2-day	cal/cm^2-day			cal/cm^2-day	cal/cm^2-day
1	603.600	812.	0.744	CLOUDY	37.5	6.2
2	545.700	818.	0.667	CLOUDY	35.7	6.5
3	608.000	820.	0.741	CLOUDY	37.7	6.2
4	604.100	820.	0.737	CLOUDY	37.5	6.2
5	592.300	817.	0.725	CLOUDY	37.2	6.3
6	588.100	811.	0.725	CLOUDY	37.1	6.3
7	607.200	804.	0.756	CLOUDY	37.6	6.2
8	511.100	791.	0.646	CLOUDY	34.6	6.8
9	586.400	779.	0.753	CLOUDY	37.0	6.3
10	543.500	752.	0.723	CLOUDY	35.7	6.6
11	554.000	729.	0.760	CLOUDY	36.0	6.5
12	533.100	706.	0.755	CLOUDY	35.3	6.6
13	529.100	678.	0.781	CLOUDY	35.2	6.6
14	516.000	663.	0.779	CLOUDY	34.7	6.7
15	497.900	643.	0.774	CLOUDY	34.1	6.8
16	377.900	580.	0.652	CLOUDY	29.2	7.7
17	317.500	544.	0.583	CLOUDY	26.2	8.3
18	328.600	499.	0.659	CLOUDY	26.8	8.2

determined. The daily values for the four rafts were averaged to determine the lake surface temperature, T_o.

The 7040 computer was used to make a table of gray body radiation per hour for a temperature range of 0 to 100 degrees Fahrenheit. The equation for the radiation emission, E, was

$$E = 0.97\ \sigma\ T_K^4$$

where

$\sigma = 8.132 \times 10^{-11}$ cal/cm^2-min-°K^4

T_K = absolute temperature of the water surface, °K.

The energy values were printed in units of calories per square centimeter per hour.

The radiation value corresponding to the average daily temperature was multiplied by the number of hours of the day that the radiation applied. Back radiation during each day of the thermal survey period was determined in this manner. Back radiation energy, Q_{bs}, for the thermal survey period was determined by summing the daily radiation values and multiplying the total by the average water surface area. The calculated back radiation from the water surface for TSP 8 as shown in Table B-IV, was

$$Q_{bs} = (6496.4 \text{ cal/cm}^2)\ (1.01707 \times 10^{11} \text{ cm}^2)$$
$$= 6.60729 \times 10^{14} \text{ cal}$$

Relative Humidity and Air Temperature

Chart traces of both relative humidity, RH, and air temperature, T_a, were integrated to obtain the area between the baseline and the trace for time intervals during thermal survey periods. The respective areas were summed over the thermal survey period. The relationships of one square inch equals 13.650 percent-hours and one square inch equals 13.7786 degree Fahrenheit-hours were used to convert area to the units of the respective quantity. Both quantities were divided by the number of hours in the thermal survey period and then added to the respective baseline value to determine the average value for the period. The baseline value for the relative humidity was 25 percent. The baseline value for the air temperature was 50 degrees Fahrenheit. An adjustment was made to the relative humidity value to correct for recorder drift. An ambient temperature correction was also made on relative humidity values for the period when the non-direct measuring sensing elements were used.

The area under the relative humidity trace for TSP 8 was 440.299 square inches. An unadjusted relative humidity was calculated as

$$\mathrm{RH} = \frac{(440.299\ \mathrm{in}^2)\ (13.650\%\text{-hrs/in}^2)}{167.5\ \mathrm{hrs}} + 25\%$$

$$= 60.9\%$$

The drift correction was +0.48 percent. There was no ambient temperature correction. Consequently the final average relative humidity value for TSP 8 was

$$RH = 60.9\% + 0.48\% = 61.4\%$$

The average air temperature, T_a, calculation was

$$T_a = \frac{(417.799\ \text{in}^2)\ (13.7786°\text{F-hrs/in}^2)}{167.5\ \text{hrs}} + 50°\text{F}$$

$$= 84.4°\text{F}$$

Water Surface Elevation

Lake stages were scaled from the two recorder charts for the beginning and ending times of the thermal survey period and at 2400 of each day. A continuous appreciable seiche was recorded at the boat dock which necessitated averaging lake stages to obtain the final value. It was estimated that maximum amount of error due to this method of averaging would be in the order of 0.0033 feet which is as close as the stage could be scaled anyway. This error would be insignificant over the thermal survey period.

Extremely high winds occurring during storms caused a massing of the water on one side of the lake with one recorder giving a higher reading and one recorder giving a lower reading than the average lake elevation. Differences in the order of 0.0165 feet occurred often. When ordinary winds of 10 to 15 miles per hour occurred, the two recorders were usually within 0.0033 to 0.0066 feet of each other.

The magnitude of this difference, 16 to 33 percent, is appreciable if compared to the average daily evaporation. However, it is only 2 to 4 percent of the evaporation for a week long thermal survey period.

Even though the recorders may not have agreed within 0.0033 to 0.0066 feet on a particular day, it does not necessarily mean the recorders were in error by this amount. It was estimated that the average error was ± 0.0033 feet. For the 1950 Water Loss Investigation at Lake Hefner, Harbeck estimated the standard error of his observation to be 0.0036 feet while using four Stevens recorders.

Precipitation

Rainfall amounts for the south station, the intake tower, and the east station were averaged to obtain the precipitation amount for energy budget calculations. Water budget calculations also considered amounts from the rain gage at the water plant. Rainfall amounts were obtained from the recorder charts or from direct stick measurement in non-recording gages. Volumetric measurements were considered to be a check for gross errors.

A summary of monthly rainfall for the different stations is shown in Table III. Rainfall distribution is observed to be widely variable between the stations. Table B-X shows the daily rainfall for TSP 8.

TABLE III

COMPARISON OF MONTHLY TOTAL RAINFALL BY STATION

Month	South Station in.	East Station in.	Intake Tower in.	Water Plant in.	Avg in.
June*	3.81	5.00	3.67	4.43	4.22
July	2.52	2.31	1.94	2.29	2.26
August	5.28	5.88	6.40	4.35	5.48
September	6.47	6.76	6.70	8.01	6.99
October**	1.11	0.99	0.77	0.91	0.95
Total	19.19	20.94	19.48	19.99	19.90

* From June 3

** To October 23 only

Rainfall temperatures were needed for the energy budget calculations. The minimum radiometer plate temperature during the rain was obtained from the recorder chart trace. Relative humidity readings from the recorder charts were observed at 5 minute intervals and averaged over the rainfall period. A similar determination was made for the average dry bulb air temperature. These data were used to calculate wet bulb air temperature. The temperature of the rainfall was then assumed to be the average of the flat plate and wet bulb temperatures.

TSP 8 had rains on July 24, 25, 27, and 28 with average amounts of 0.05, 0.58, 0.95 and 0.063 inch with average rainfall temperatures of 24.44, 20.84, 20.98, and 22.50 degrees centigrade, respectively.

Surface Inflow

Surface inflow data were obtained from the U.S. Geological Survey. Weighted average flow rates in cubic feet per second had been calculated for each day. Hourly temperatures in degrees Fahrenheit were obtained from the intake canal recorder chart and averaged for daily or the appropriate time intervals.

Most of the inflow shown in Figure 10 occurred in June when the lake surface was raised almost to spillway elevation by releasing water from Canton Reservoir. The maximum flow for one day was 1150 cubic feet per second and was

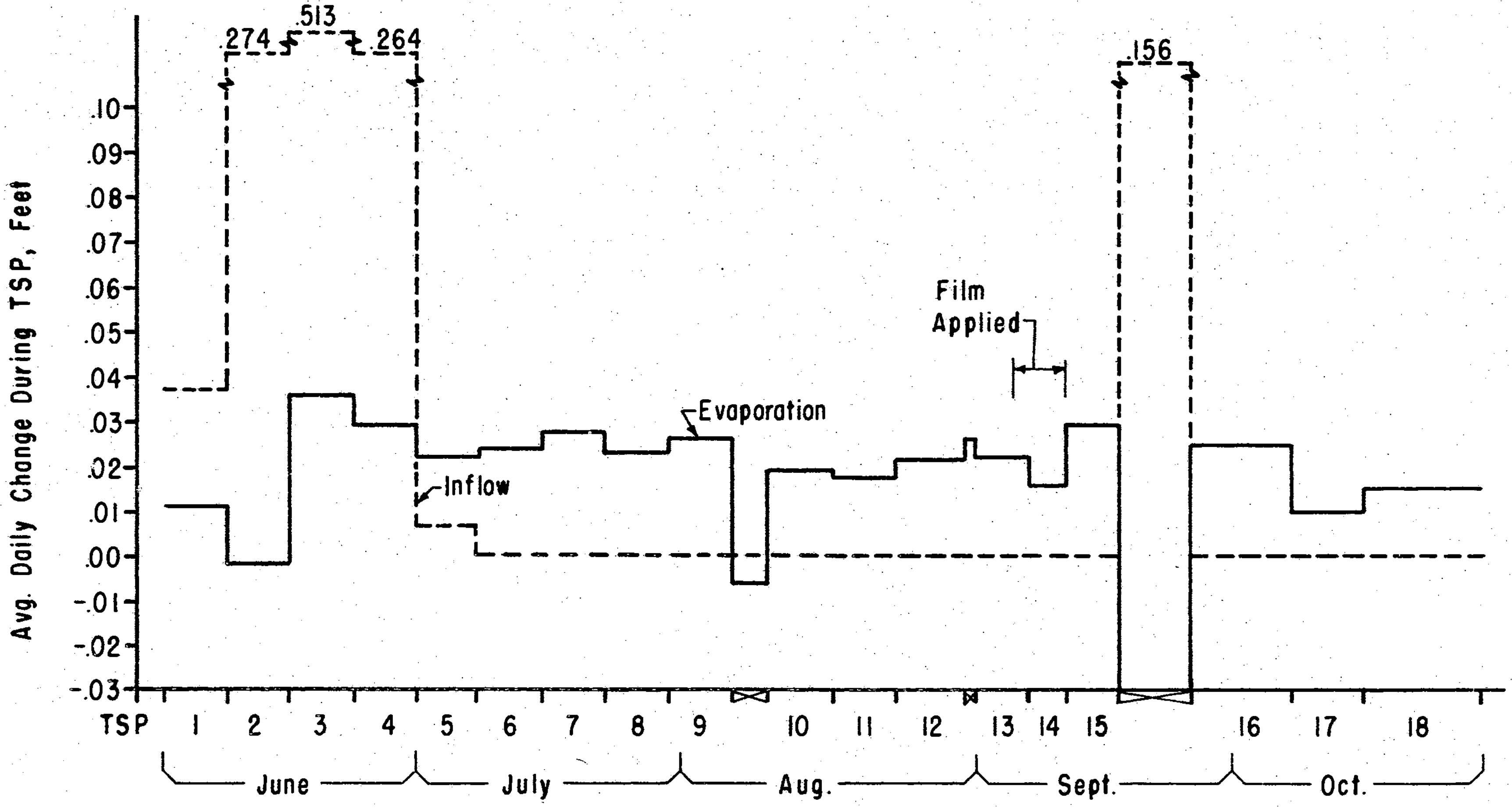

Figure 10. Influence on Lake Stage of the Inflow Through the Supply Canal and the Water Budget Evaporation During the 1965 Study.

measured with the lower gage. Another large inflow occurred from September 20 to 22 during another release. The maximum flow for one day was 871 cubic feet per second. Flow was measured with the upper gage for the September flow. Other than during periods of intentional release, inflow was quite small and probably was due largely to leakage at the gates to the inverted siphon which supplies water to the canal.

Inflow rate was converted to volume and divided by the lake surface area at 2400 of each day to obtain daily stage change due to inflow for the water budget. Table B-X shows the calculation of total inflow for TSP 8.

Outflow

Water plant withdrawals, golf course withdrawals, and seepage comprised the outflow considered in the water budget. The energy budget computations neglected seepage and golf course withdrawals due to lack of knowledge of the temperatures and due to the small magnitude of the quantities.

Outflow rates and temperatures for the water plant withdrawals were obtained from water plant records. The average daily flow was recorded in units of million gallons per day. The temperature of the outflow was assumed constant for the day.

Daily seepage flow data obtained from the Oklahoma City Water Department were recorded in cubic feet per second.

Golf course withdrawal volumes, in acre-feet, were calculated by multiplying the pump running time by the pump capacity with no consideration of head losses due to friction and elevation change. The pumps were operated by automatic timers. A fairly uniform program of irrigation was followed.

It was necessary to assume an average usage before August 20 due to lack of pump operation records before that date. Inasmuch as the amount used decreased after September 1, the average for August 20 to 31 was used for the period when timer records were lacking.

For use in the water budget all outflow volumes were converted to depth change, in feet, by dividing the volume by the lake surface area at 2400 of the particular day. Total depth change due to outflow for each thermal survey period was obtained by summing the daily values. Table B-X shows the calculation of the totals for the outflow components for TSP 8.

Advected Energy

The advected energy term, Q_v, is the net energy gained due to precipitation and surface inflow entering the reservoir, and water plant withdrawals from the reservoir.

Internal energy of each advected volume of water was calculated by the expression

$$Q = V\rho c_p \, (T - T_b)$$

where

Q = advected energy, cal
V = advected volume, cm^3
ρ = mass density of the water, g/cm^3
c_p = constant pressure specific heat, cal/g-°C
T = advected water temperature, °C
T_b = base temperature of 0°C

The advected energy components calculated for TSP 8 are shown in Tables B-V, B-VI, and B-VII.

Bowen Ratio

Bowen Ratio was calculated using Equation 10. Daily atmospheric pressures in inches of mercury were obtained from the U.S. Weather Bureau and averaged to determine the pressure for the thermal survey period. A standard height correction was applied to the pressure to adjust for elevation difference between Will Rogers Airport and Lake Hefner. No attempt was made to account for horizontal variations of the atmosphere. Table IV shows the calculation of Bowen Ratio by thermal survey periods.

Stored Energy

Temperature profiles were obtained at thirty-one stations throughout the lake. A computer was used to determine the internal energy of the reservoir from the profiles. The

TABLE IV

TABULATION OF PERTINENT QUANTITIES AND CALCULATION OF BOWEN'S RATIO, R, BY THERMAL SURVEY PERIODS FOR LAKE HEFNER

TSP	Avg T_o	Avg T_a	Avg RH	Avg e_o	Avg e_s	Avg e_a	$\Delta T = T_o - T_a$	$\Delta e = e_o - e_a$	P	R
	°C	°C	%	mb	mb	mb	°C	mb	mb	
1	23.7	24.7	66.2	29.298	31.109	20.59	-1.0	8.71	970.14	-0.068
2	25.7	24.3	71.9	33.016	30.373	21.84	1.4	11.18	970.62	0.074
3	25.4	25.2	64.8	32.434	32.050	20.77	0.2	11.66	974.07	0.010
4	25.6	27.2	63.7	32.821	36.070	22.98	-1.6	9.84	974.34	-0.097
5	26.9	28.7	55.1	35.440	39.365	21.69	-1.8	13.75	972.14	-0.078
6	27.3	30.3	52.4	36.282	43.166	22.62	-3.0	13.66	972.14	-0.130
7	27.9	30.9	46.7	37.576	44.672	20.86	-3.0	16.72	973.16	-0.107
8	27.7	29.1	61.4	37.140	40.287	24.74	-1.4	12.40	973.73	-0.067
9	27.1	26.5	47.7	35.859	34.615	16.51	0.6	19.35	973.43	0.018
10	26.9	26.4	65.2	35.440	34.411	22.45	0.5	12.99	974.92	0.023
11	26.4	27.6	72.3	34.411	36.924	26.70	-1.2	7.71	971.53	-0.092
12	26.8	28.1	69.4	35.232	38.017	26.38	-1.3	8.85	971.90	-0.087
13	25.4	25.8	62.1	31.434	33.212	20.62	-0.4	11.81	971.63	-0.020
14	26.4	28.6	56.4	34.411	39.137	22.07	-2.2	12.34	973.49	-0.106
15	25.7	28.4	51.2	33.016	38.686	19.81	-2.7	13.21	969.40	-0.121
16	21.3	17.7	63.7	25.323	20.244	12.90	3.6	12.42	974.24	0.172
17	19.8	18.3	58.4	23.085	21.023	12.28	1.5	10.80	973.26	0.082
18	19.2	19.0	63.2	22.240	21.964	13.88	0.2	8.36	972.95	0.014

temperatures as obtained from the thermometer had to be corrected from calibration charts. Least square lines were fitted to the calibration points over four 5 degree Centigrade intervals between 15 and 35 degress. The least square lines were written into the computer program so that raw temperature data was corrected by the computer.

Water stage at the time corresponding to the midpoint of each thermal survey was scaled from the stage recorder charts. The computer program also included the stage-area equations for each 5 foot interval of stage change. Density and specific heat were assumed to be unity. All temperatures at a particular depth were averaged and multiplied by the area at that depth. Energy content by layers was computed by considering the layers to be trapesoidal volumes. Total reservoir energy was obtained by summing the energies of all layers.

Tables B-VIII and B-IX show the results of the computer analysis of the July 22 and July 29 thermal surveys. Energy in the top layer of the reservoir was computed as follows:

Upper base (surface) = (26.92°C)(2519.64 ac)
= 67828.71 ac-°C

Lower base (2 1/2 ft depth) = (26.95°C)(2401.04 ac)
= 64708.03 ac-°C

Layer energy = 0.5 (67828.71 ac-°C + 64708.03 ac-°C)
(2.5 ft)(1.23349 x 10^9 cm^3/ac-ft)
(1 g/cm^3)(1 cal/g-°C) = 2.04x10^{11}cal

The energy content of each subsequent layer was calculated similarly.

The program for stored energy is presented as Table C-I. The weighted average temperature of the lake for the thermal survey was necessary for thermal expansion corrections. The area-temperature products were summed and divided by the area summation to obtain the temperature.

Wind Speed

Wind travel in miles at each of the four rafts for the thermal survey period was determined by obtaining the difference in odometer readings from the start to the end of the period. Average wind speed was obtained by dividing the wind travel by the number of hours in the thermal survey period. Average wind speed for the four rafts was then converted to units of kilometers per day for calculating the mass transfer coefficient.

Water Budget Evaporation

Equation 6 was modified to have units representative of depth change rather than volume for the purpose of computing the evaporation. Components of the equation were determined on a daily basis in feet. The assumption that density was constant could lead to a slight error in evaporation determination. Therefore, a thermal expansion correction was made using the average weighted temperature from the thermal survey.

The procedure for evaluating the stage change due to thermal expansion for TSP 8 was as follows: Specific volumes relative to 0 degrees Centigrade were determined at the start and end of the thermal survey period. The weighted average temperatures for July 22 and July 29 were 26.78 and 26.97 degrees Centigrade, respectively, and the specific volumes relative to 0 degrees Centigrade were 1.00328 and 1.00333 cubic centimeters, respectively. A volume ratio was obtained by dividing 1.00333 by 1.00328 and the quantity one was subtracted from the ratio to obtain the unit variable expansion. Multiplying the expansion by the reservoir volume of July 29, and dividing by the surface area, resulted in the calculation

$$\text{EXP} = \frac{[(1.00333/1.00328)-1]\ [73367\ \text{ac-ft}]}{2511\ \text{ac}}$$

$$= 0.0015\ \text{ft}$$

The effect of thermal expansion was small until September 10. The largest expansion, -0.197 inch, occurred during thermal survey period 15.

Table B-X lists the pertinent quantities and the computed water budget evaporation for TSP 8. The water budget evaporation computation summary is shown in Table V.

TABLE V

SUMMARY OF WATER BUDGET EVAPORATION COMPUTATION BY THERMAL SURVEY PERIODS

TSP	Stage Change	Water Plant With-drawal	Irri-gation With-drawal	Seepage	Inflow	Rain	Thermal Expansion	Evap	Evap
	ft	ft	ft	ft	ft	ft	ft	ft	in
1	0.0230	0.1678	0.0041	0.0033	0.2581	0.0115	0.0050	0.0764	0.9168
2	1.9620	0.1093	0.0042	0.0042	1.9180	0.1417	0.0050	-0.0150	-0.1800
3	3.3370	0.1164	0.0042	0.0033	3.5928	0.1138	0.0044	0.2501	3.0012
4	1.6070	0.1252	0.0042	0.0041	1.8499	0.0854	0.0071	0.2019	2.4228
5	-0.2290	0.1669	0.0042	0.0033	0.0469	0.0479	0.0050	0.1544	1.8528
6	-0.3480	0.1799	0.0042	0.0034	0.0033	0.0008	0.0003	0.1649	1.9788
7	-0.4100	0.2113	0.0042	0.0027	0.0008	0.0000	-0.0006	0.1920	2.3040
8	-0.1770	0.1516	0.0042	0.0030	0.0010	0.1379	0.0015	0.1586	1.9032
9	-0.2500	0.0538	0.0042	0.0035	0.0010	0.0000	-0.0061	0.1834	2.2008
10	-0.1900	0.0621	0.0041	0.0063	0.0028	0.0169	-0.0035	0.1337	1.6044
11	-0.1610	0.0619	0.0043	0.0054	0.0011	0.0246	0.0049	0.1200	1.4400
12	-0.2300	0.0786	0.0038	0.0064	0.0013	0.0306	-0.0043	0.1688	2.0256
13	-0.0850	0.0059	0.0010	0.0054	0.0008	0.0373	-0.0014	0.1094	1.3128
14	-0.0620	0.0000	0.0027	0.0032	0.0007	0.0000	0.0049	0.0617	0.7404
15	-0.2370	0.0360	0.0043	0.0045	0.0005	0.0031	-0.0164	0.1794	2.1528
16	-0.2070	0.0000	0.0019	0.0077	0.0043	0.0040	-0.0130	0.1927	2.3124
17	-0.0920	0.0000	0.0020	0.0090	0.0011	0.0004	-0.0047	0.0778	0.9336
18	-0.1600	0.0000	0.0015	0.0150	0.0023	0.0612	-0.0081	0.1989	2.3868
Total	4.0910	1.5267	0.0633	0.0937	7.6867	0.7171	-0.0200	2.6091	31.3092

Energy Budget Evaporation

Evaporation by the energy budget method was determined using Equation 9. The pertinent quantities and the evaporation determination are shown in Table VI. All quantities were entered algebraically to evaluate the expression.

Mass Transfer Coefficient

Evaporation was computed by two different methods. Therefore values of the mass transfer coefficient, N, were determined from both the energy budget and water budget results. The expression for calculating N in units of centimeter per kilometer per millibar was

$$N = \frac{E}{u_2 \Delta e}$$

where

E = evaporation rate, cm/day

u_2 = wind speed at 2-meter height, km/day

$\Delta e = e_o - e_a$ = vapor pressure deficit (evaluated in Bowen Ratio Computation), mb

Table VII shows the calculation table for determining N from the water budget results and Table VIII shows a similar table using energy budget results.

TABLE VI

ENERGY BUDGET SUMMARY FOR LAKE HEFNER - 1965

TSP	ENERGY								Bowen Ratio	Avg Water Surf Temp	Heat Of Vaporization	Specific Heat	Avg Density	Evap	Surf Area	Evap	Evap
	Q_s	Q_a	Q_r	Q_{ar}	Q_{bs}	Q_n	Q_v	Q_o	R	T_o	L	C_p	ρ	E	A	E	E
	cal x 10^{14}									°C	cal/g	cal/g-°C	g/cm^3	cm^3	cm^{2}x10^{11}	cm	in
1	3.7190	5.3780	0.2312	0.1613	5.4340	3.2705	0.0944	0.7046	-0.068	23.7	582.90	0.99841	0.99739	4.7047	0.9044	5.2020	2.0480
2	3.5200	5.6193	0.2305	0.1686	5.8474	2.8929	1.4141	1.8632	0.074	25.7	581.85	0.99823	0.99689	3.7682	0.9215	4.0892	1.6099
3	4.1331	5.8701	0.2560	0.1761	6.1392	3.4320	2.7573	2.9817	0.010	25.4	581.90	0.99825	0.99697	5.2479	0.9711	5.4041	2.1276
4	4.3792	6.5447	0.2722	0.1963	6.5598	3.8956	1.4923	2.1372	-0.097	25.6	581.88	0.99824	0.99691	5.9179	1.0326	5.7311	2.2563
5	4.2951	6.4812	0.2697	0.1944	6.6804	3.6318	-0.0588	0.2234	-0.078	26.9	581.10	0.99815	0.99657	5.9740	1.0359	5.7670	2.2705
6	4.2436	6.6299	0.2674	0.1989	6.6823	3.7249	-0.1418	-0.0034	-0.130	27.3	580.90	0.99812	0.99646	6.7574	1.0309	6.5549	2.5807
7	4.3514	6.5241	0.2697	0.1957	6.6854	3.7247	-0.1783	-0.4966	-0.107	27.9	580.55	0.99809	0.99629	7.4286	1.0238	7.2559	2.8566
8	3.6277	6.4524	0.2453	0.1936	6.6073	3.0339	-0.0376	0.1044	-0.067	27.7	580.65	0.99810	0.99634	5.0976	1.0171	5.0119	1.9732
9	4.1731	6.0425	0.2634	0.1813	6.5676	3.2034	-0.0436	-0.9319	0.018	27.1	581.05	0.99814	0.99651	6.6380	1.0137	6.5483	2.5781
10	3.8507	6.1098	0.2526	0.1833	6.5270	2.9976	-0.0367	-0.3573	0.023	26.9	581.10	0.99815	0.99657	5.3590	1.0151	5.2793	2.0785
11	3.8520	6.1780	0.2503	0.1853	6.3600	3.2344	-0.0329	0.4053	-0.092	26.4	581.40	0.99818	0.99670	5.0615	1.0114	5.0045	1.9703
12	4.2984	7.2165	0.2847	0.2165	7.4099	3.6038	-0.0416	-0.2343	-0.087	26.8	581.15	0.99815	0.99659	6.8351	1.0078	6.7822	2.6702
13	2.6473	4.2461	0.1760	0.1274	4.5172	2.0728	0.0174	-0.3008	-0.020	25.4	581.90	0.99825	0.99697	4.0266	1.0048	4.0073	1.5777
14	2.0608	3.5967	0.1387	0.1079	3.6533	1.7575	0.0005	0.4422	-0.106	26.4	581.40	0.99818	0.99670	2.4174	1.0037	2.4085	0.9482
15	3.0944	5.3722	0.2119	0.1612	5.6340	2.4595	-0.0256	-1.9444	-0.121	25.7	581.80	0.99823	0.99689	8.1778	1.0010	8.1696	3.2164
16	3.0645	5.9886	0.2370	0.1797	6.9244	1.7120	0.0037	-2.0134	0.172	21.3	584.20	0.99865	0.99795	5.2932	1.0351	5.1137	2.0133
17	2.6013	6.1181	0.2149	0.1835	6.8542	1.4667	0.0006	-0.8361	0.082	19.8	585.00	0.99886	0.99827	3.5349	1.0321	3.4250	1.3484
18	4.4203	9.5273	0.3607	0.2858	11.1595	2.1416	0.0441	-1.4869	0.014	19.2	585.35	0.99894	0.99839	6.0035	1.0297	5.8303	2.2954

TABLE VII

SUMMARY BY THERMAL SURVEY PERIODS OF THE MASS TRANSFER COEFFICIENT N DETERMINED FROM WATER BUDGET EVAPORATION DATA

	Wind Speed	Vapor Pressure Deficit	Evap.		Mass Transfer Coefficient
TSP	U_2	$e_o - e_a = \Delta e$	E	$U_2 \Delta e$	N
	Km/day	mb	cm/day	Km-mb/day	cm/Km-mb x 10^{-5}
1	515.64	8.71	0.3419	4491.19	7.6123
2	332.56	11.18	-0.0653	3717.98	-1.7557
3	473.54	11.66	1.0889	5521.42	19.7213
4	560.44	9.84	0.8766	5514.73	15.8948
5	424.10	13.75	0.6723	5831.32	11.5298
6	437.23	13.66	0.7181	5972.54	12.0227
7	424.87	16.72	0.8359	7103.80	11.7671
8	344.14	12.40	0.6927	4267.38	16.2315
9	325.60	19.35	0.7963	6300.43	12.6387
10	341.83	12.99	0.5839	4440.32	13.1510
11	385.86	7.71	0.5321	2974.96	17.8869
12	496.32	8.85	0.6431	4392.46	14.6416
13	517.18	11.81	0.6698	6107.90	10.9661
14	403.62	12.34	0.4727	4980.73	9.4905
15	640.39	13.21	0.8809	8459.59	10.4127
16	444.57	12.42	0.7498	5521.52	13.5797
17	244.11	10.80	0.2987	2636.35	11.3302
18	500.57	8.36	0.4877	4184.78	11.6536

TABLE VIII

SUMMARY BY THERMAL SURVEY PERIODS OF THE MASS TRANSFER COEFFICIENT N DETERMINED FROM ENERGY BUDGET EVAPORATION DATA

	Wind Speed	Vapor Pressure Deficit	Evap.		Mass Transfer Coefficient
TSP	U_2	$e_o-e_a=\Delta e$	E	$U_2\Delta e$	N
	Km/day	mb	cm/day	Km-mb/day	cm/Km-mb x 10^{-5}
1	515.64	8.71	0.7636	4491.19	17.0018
2	332.56	11.18	0.5842	3717.98	15.7119
3	473.54	11.66	0.7720	5521.42	13.9822
4	560.44	9.84	0.8163	5514.73	14.8020
5	424.10	13.75	0.8239	5831.32	14.1283
6	437.23	13.66	0.9364	5972.54	15.6789
7	424.87	16.72	1.0365	7103.80	14.5913
8	344.14	12.40	0.7181	4267.38	16.8282
9	325.60	19.35	0.9327	6300.43	14.8039
10	341.83	12.99	0.7564	4440.32	17.0359
11	385.86	7.71	0.7279	2974.96	24.4687
12	496.32	8.85	0.8478	4392.46	19.3010
13	517.18	11.81	0.8048	6107.90	13.1767
14	403.62	12.34	0.6053	4980.73	12.1519
15	640.39	13.21	1.3159	8459.59	15.5554
16	444.57	12.42	0.6528	5521.52	11.8233
17	244.11	10.80	0.4315	2636.35	16.3667
18	500.57	8.36	0.4463	4184.78	10.6658

CHAPTER VII

RESULTS

Evaporation Rates

Average daily evaporation rates as determined by the water budget method and energy budget method are tabulated in Table IX. These data are shown graphically in Figures 11 and 12.

Evaporation rates determined by the water budget method for thermal survey periods one through four is of doubtful accuracy. During these periods the lake was being filled by a release from Canton Reservoir. The inflow canal lacked sufficient accuracy to provide a good measure of high inflow rates. This resulted in erratic values for evaporation. Negative evaporation was indicated for TSP 2 and for the time interval between TSP 15 and TSP 16. High rates of inflow occurred during these periods. Unusually high evaporation rates were indicated for TSP 3.

One factor which contributed to the error in measuring high inflow rates may be the lack of sensitivity of the stage recorder which had a 1:6 height ratio. Flow turbulence in the channel caused the recorder pen to vary ± 0.1 foot on the graph. That amount during the maximum flow

TABLE IX

SUMMARY BY THERMAL SURVEY PERIODS OF AVERAGE EVAPORATION RATES COMPUTED FROM WATER BUDGET AND ENERGY BUDGET DETERMINATIONS

TSP	Water Budget Evaporation Rate cm/day	Energy Budget Evaporation Rate cm/day
1	0.3419	0.7636
2	-0.0653	0.5842
3	1.0889	0.7720
4	0.8766	0.8163
5	0.6723	0.8239
6	0.7181	0.9364
7	0.8359	1.0365
8	0.6927	0.7181
9	0.7963	0.9327
10	0.5839	0.7564
11	0.5321	0.7279
12	0.6431	0.8478
13	0.6698	0.8048
14	0.4727	0.6053
15	0.8809	1.3159
16	0.7498	0.6528
17	0.2987	0.4315
18	0.4877	0.4463

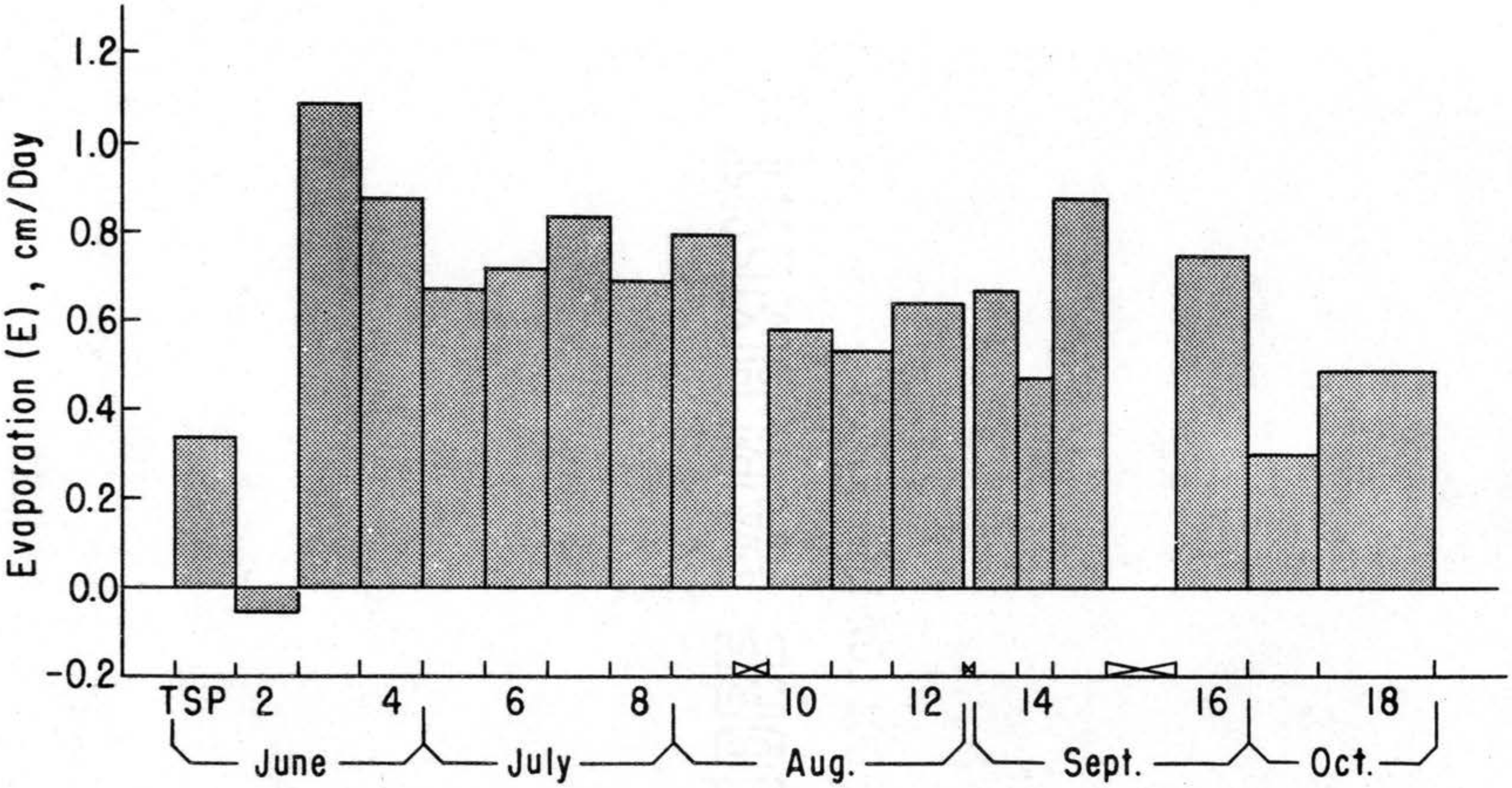

Figure 11. Evaporation Computed by the Water Budget Method for the 1965 Lake Hefner Investigation.

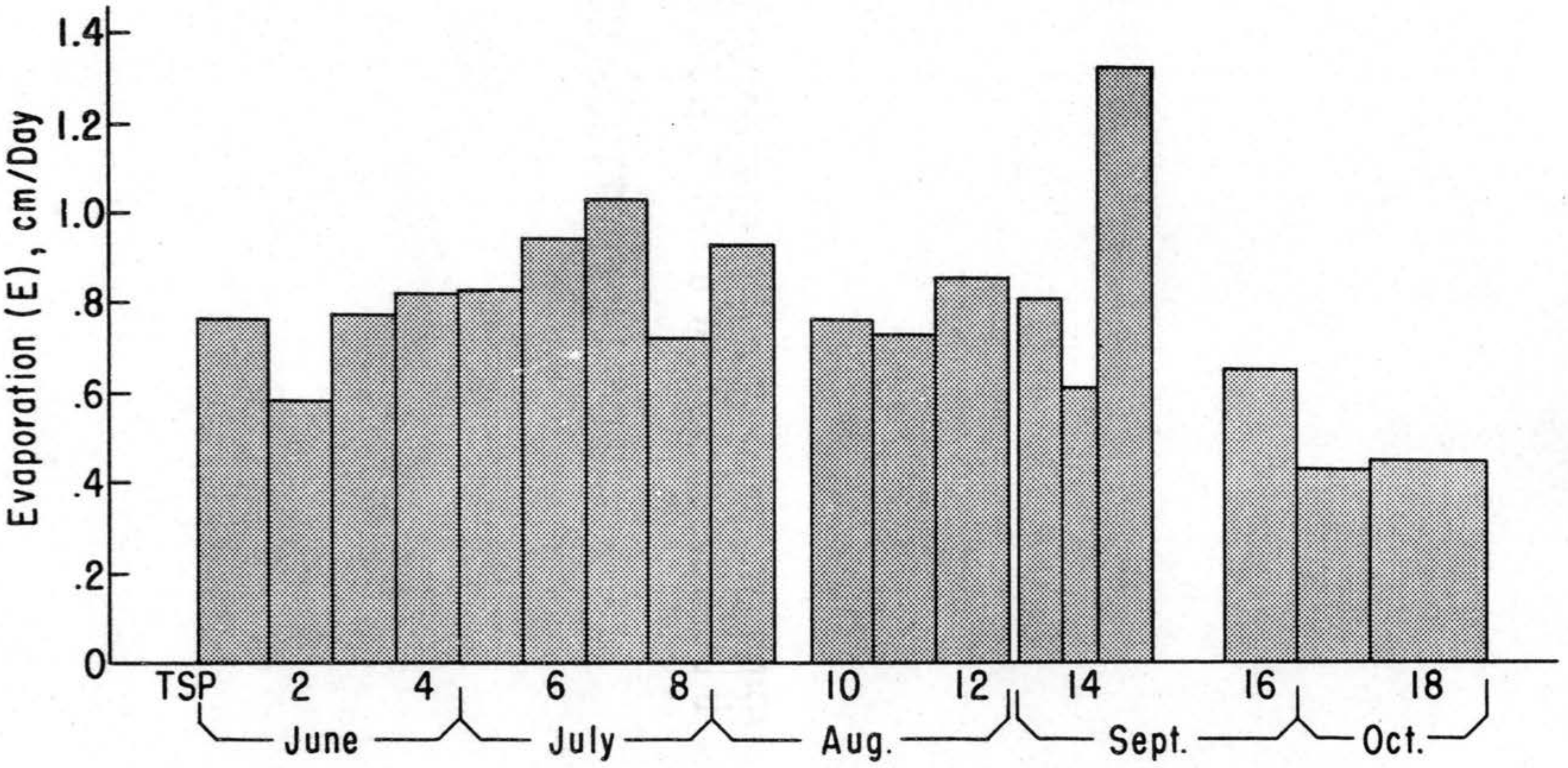

Figure 12. Evaporation Computed by the Energy Budget Method for the 1965 Lake Hefner Investigation.

which occurred during the period September 20 to 22 would have caused an error of approximately 200 cubic feet per second.

Harbeck and Kennon reported that the error in monthly evaporation computed from the water budget did not exceed 5 percent during the 1950-51 Lake Hefner Investigation. It is believed that the same water budget error was applicable to the 1965 Lake Hefner study except when large inflows occurred.

Since there is an element of doubt concerning the accuracy of inflow measurements, the energy budget method is considered superior to the water budget method during periods of high inflow. The reason for this is that the inflow exerts more influence on the results of the water budget computation than it does on the energy budget computation. For example deleting the inflow from the water budget of TSP 3 results in a 43.1-inch difference in the evaporation while the same deletion in the energy budget would result in only a 0.713-inch difference.

Energy budget evaporation is plotted against water budget evaporation in Figure 13. Evaporation amounts for thermal survey periods one through four were not plotted due to the doubtful measurement of the inflow. Evaporation amounts for TSP 14 were not plotted either because during this period efforts were made to suppress evaporation by use of a monolayer.

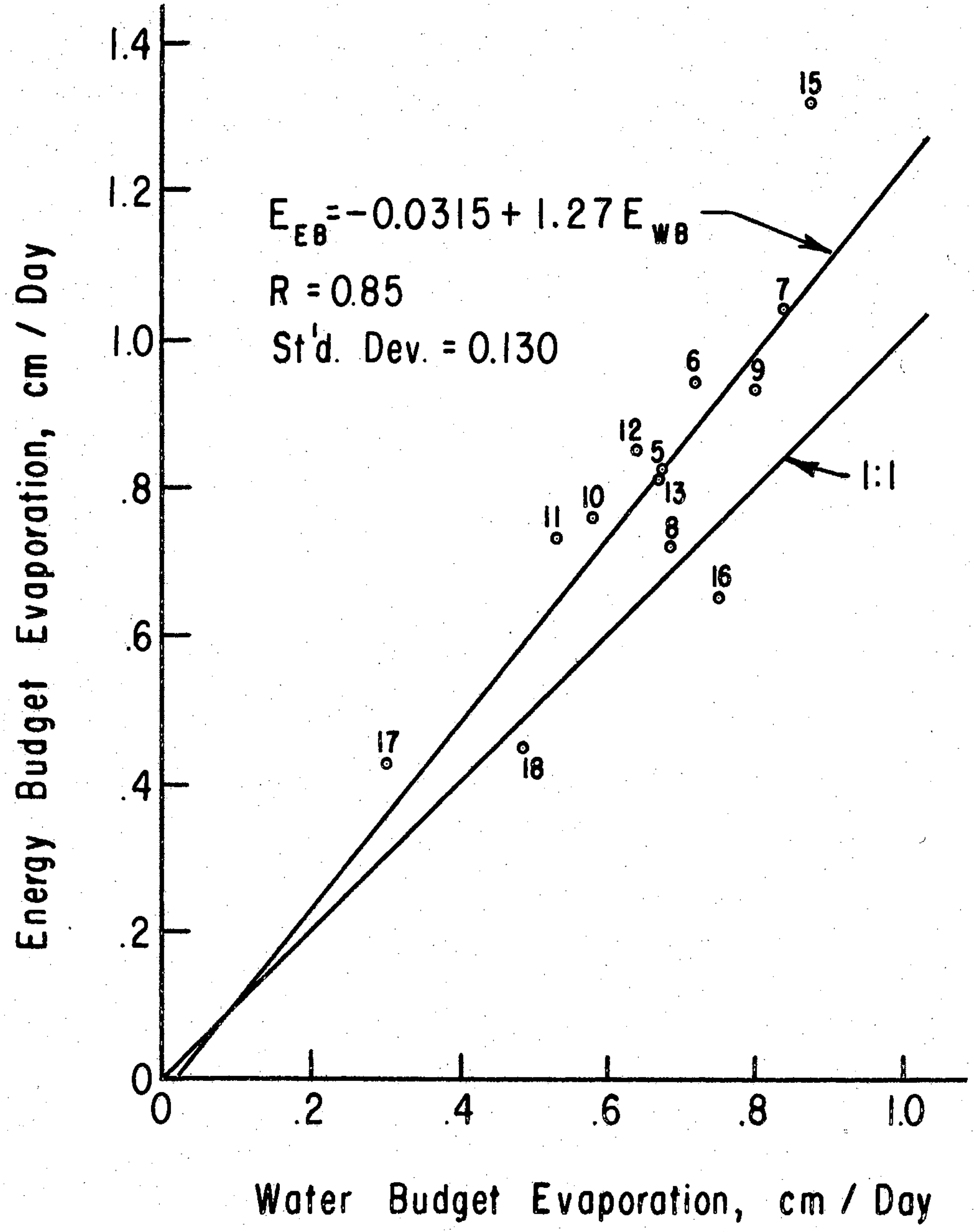

Figure 13. Relationship Between the Energy Budget Evaporation, E_{EB}, and the Water Budget Evaporation, E_{WB}, for the 1965 Lake Hefner Investigation.

Theoretically the points in Figure 13 should have plotted on the one-to-one line as both methods were computing the same quantity. Except for TSP's 16 and 18, the energy budget estimate was higher than the water budget value. The equation for this relation was

$$E_{EB} = -0.0315 + 1.27\ E_{WB}$$

Energy Budget Parameters

Energy gain of the reservoir due to radiation is considered to be the driving force of evaporation, providing the energy necessary for the evaporation process. Variations of the energy flux for the study period given in Table X are shown in Figure 14. Back radiation from the water surface, Q_{bs}, and atmospheric radiation, Q_a, were the most significant radiation influences. The solar radiation, Q_s, amounted to approximately one-third the amount of atmospheric radiation or back radiation. The reflected short-wave or solar radiation, Q_r, and the reflected atmospheric radiation, Q_{ar}, were appreciably smaller in comparison to the other radiations. Large amounts of sky cover during TSP 2 and TSP 8 probably explains the drop in solar radiation during those periods.

Figure 15 shows how the change in the stored energy is related to the advected energy. In the first four thermal survey periods the change in stored energy is

TABLE X

RADIATION SUMMARY FOR LAKE HEFNER - 1965

TSP	RADIATION					
	Q_s	Q_a	Q_r	Q_{ar}	Q_{bs}	Q_n
	cal/cm^2-day					
1	603.6	872.9	37.5	26.2	882.0	530.8
2	545.7	871.1	35.7	26.1	906.5	448.5
3	608.0	863.5	37.7	25.9	903.1	504.9
4	604.1	902.8	37.5	27.1	904.8	537.3
5	592.3	893.8	37.2	26.8	921.3	500.8
6	588.1	918.7	37.1	27.6	926.0	516.2
7	607.2	910.3	37.6	27.3	932.9	519.7
8	511.1	909.0	34.6	27.3	930.8	427.4
9	586.4	849.0	37.0	25.5	922.8	450.1
10	543.5	862.4	35.7	25.9	921.3	423.1
11	554.0	888.5	36.0	26.7	914.7	465.2
12	533.1	895.1	35.3	26.9	919.1	447.0
13	529.1	848.7	35.2	25.5	902.9	414.3
14	516.0	900.5	34.7	27.0	914.7	440.1
15	497.9	864.5	34.1	25.9	906.6	395.8
16	377.9	738.6	29.2	22.2	854.0	211.1
17	317.5	746.8	26.2	22.4	836.7	179.0
18	328.6	708.3	26.8	21.2	829.7	159.2

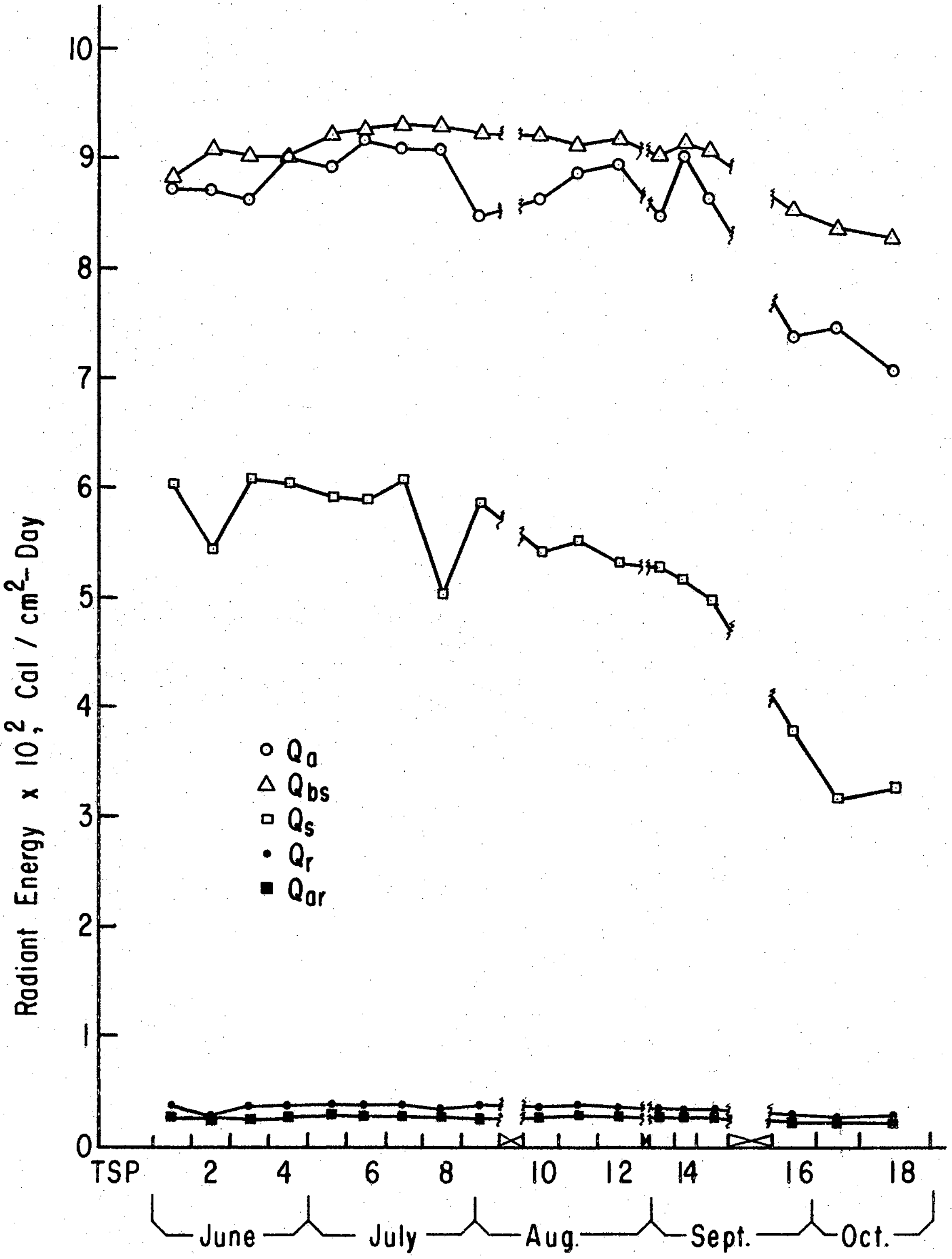

Figure 14. Variation of the Several Radiant Energy Flux Rates for the 1965 Lake Hefner Investigation Period.

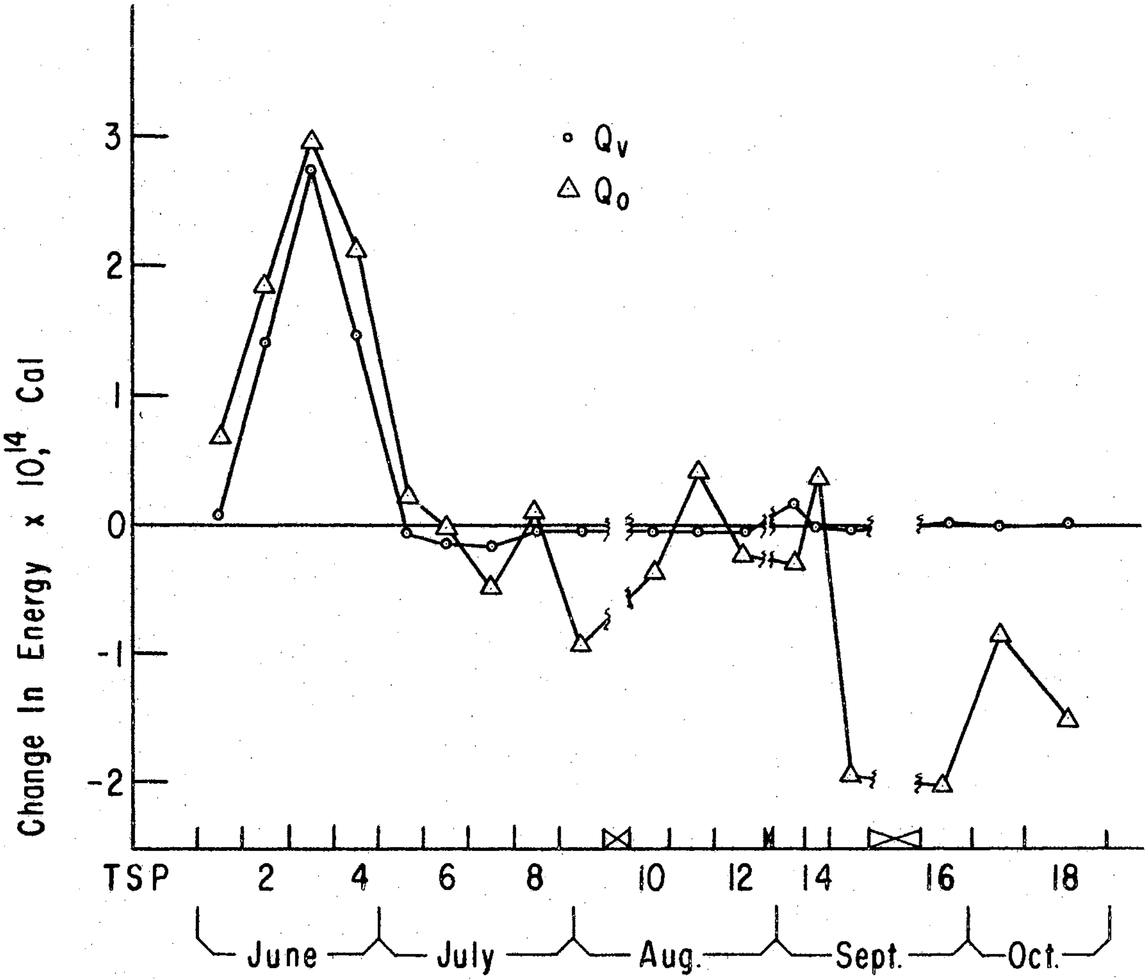

Figure 15. Variation of the Change in Stored Energy, Q_o, and the Advected Energy, Q_v, for the 1965 Lake Hefner Investigation.

greatly affected by the advected energy, mainly that due to inflow. Both TSP 15 and TSP 16 show large negative changes in stored energy with only small changes in advected energy. TSP 15 had a high evaporation rate as shown in Figures 11 and 12. Average wind speeds for the two periods were high and both periods had small amounts of cloud cover. TSP 15 had a high average air temperature and the highest average wind speed of any period during the study. TSP 16 air temperature averaged below the water surface temperature by at least 3 degrees Centigrade.

An integral part of determining the change in stored energy in the reservoir was to measure the temperature profiles encompassing thermal survey periods. Figures 16 through 20 show the results of the thermal surveys. It can be seen in Figures 19 and 20 that the temperature profiles decreased in both TSP 15 and TSP 16. The temperature profile decreased during TSP 15 even though the average air temperature was higher than the average water surface temperature.

The higher temperatures measured near the surface of some of the profiles were the results of calm periods immediately before or during the thermal survey. Wind speeds during these calm periods were approximately 5 to 6 miles per hour. Normally the high winds kept the water mixed so that temperatures were very uniform depthwise.

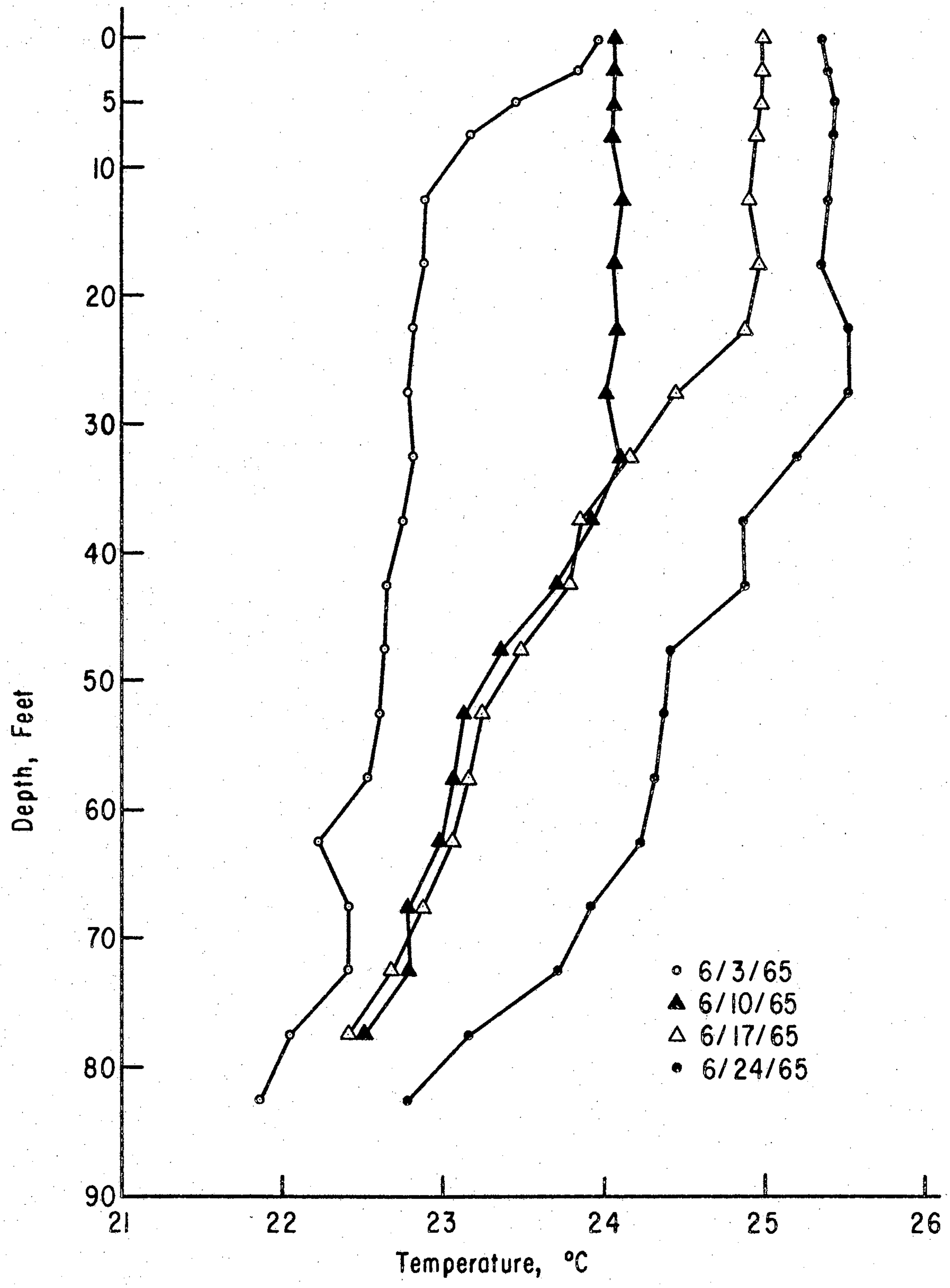

Figure 16. Lake Temperature Profiles for the June Month of the 1965 Lake Hefner Investigation.

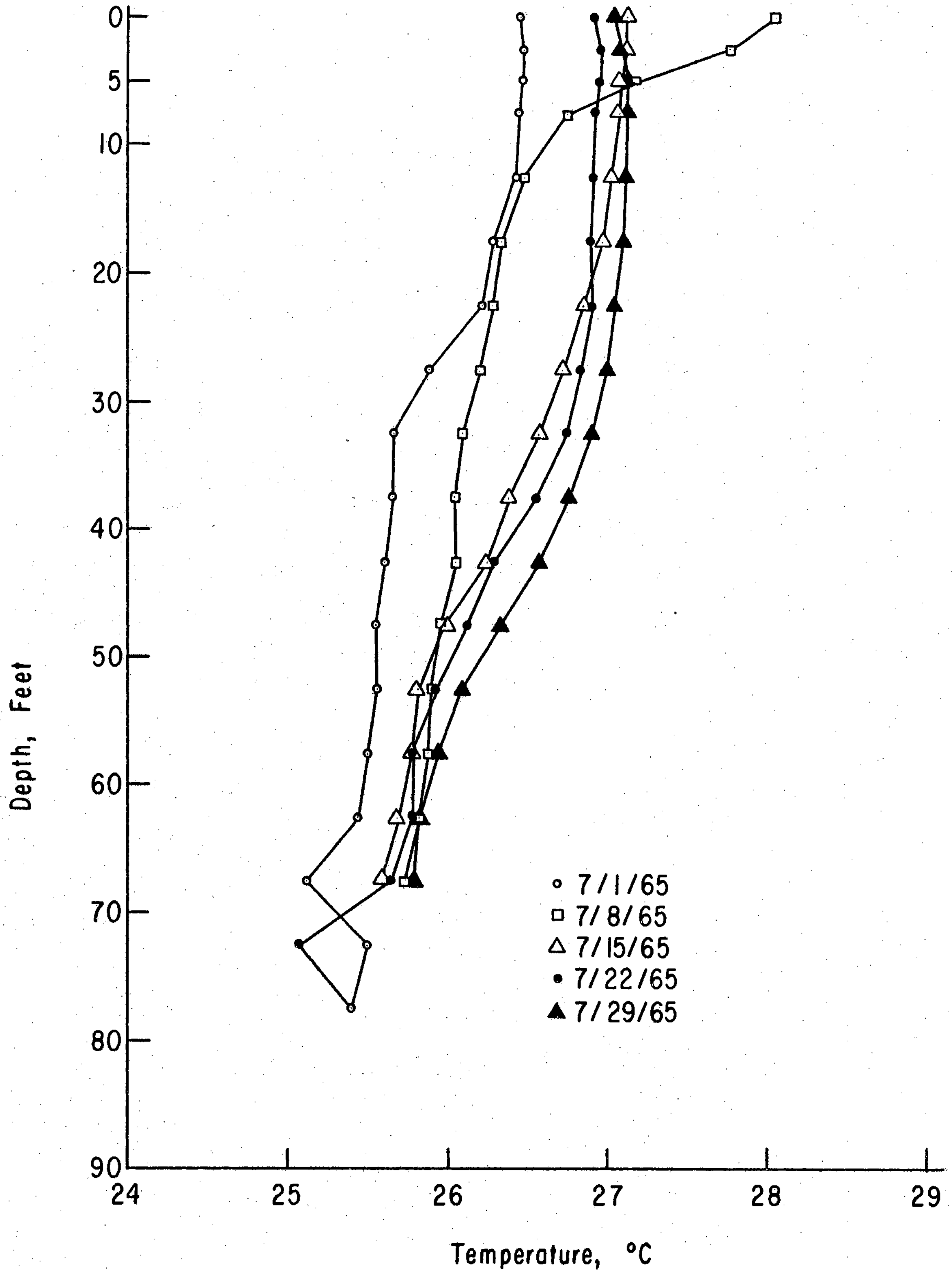

Figure 17. Lake Temperature Profiles for the July Month of the 1965 Lake Hefner Investigation.

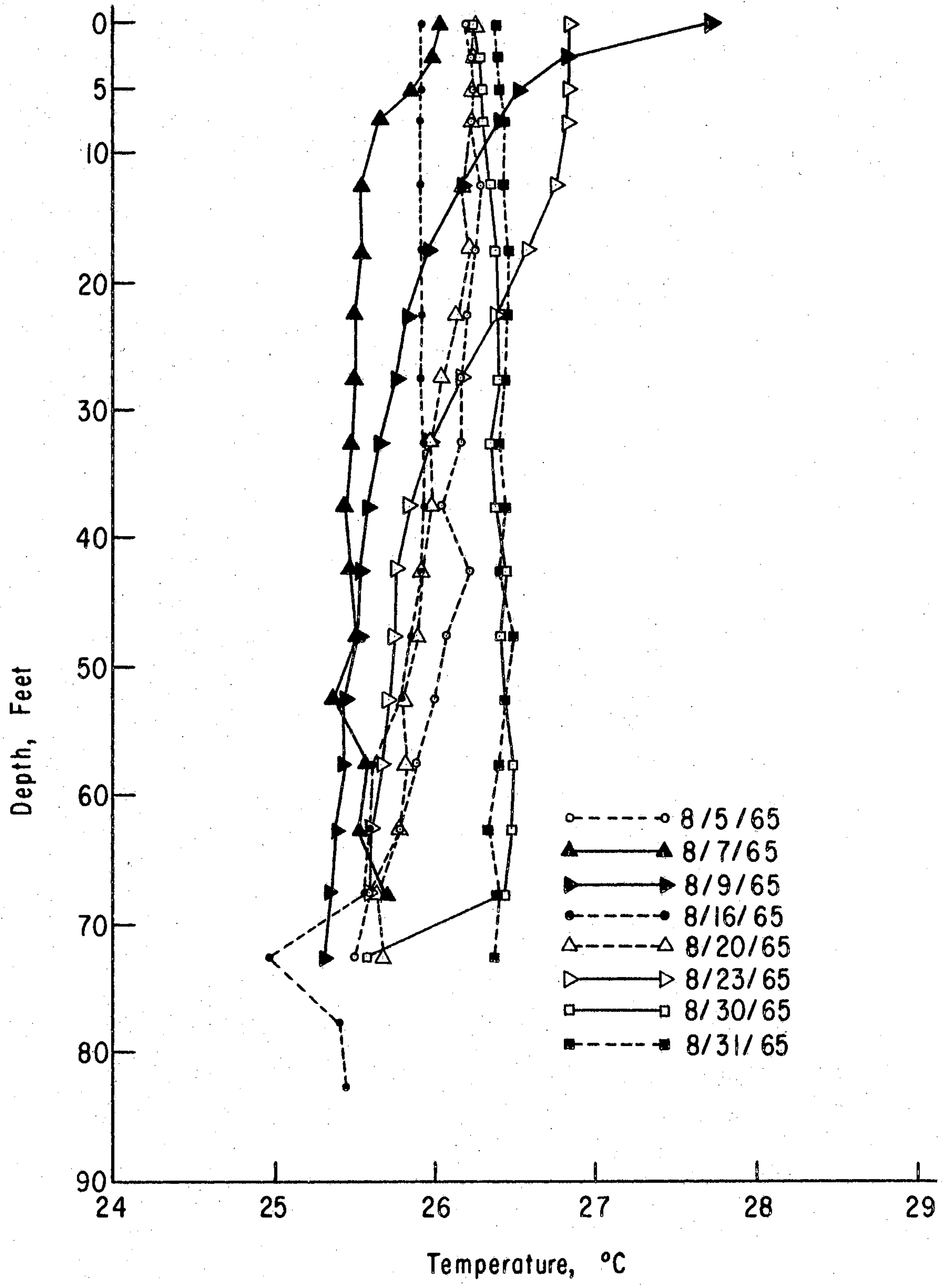

Figure 18. Lake Temperature Profiles for the August Month of the 1965 Lake Hefner Investigation.

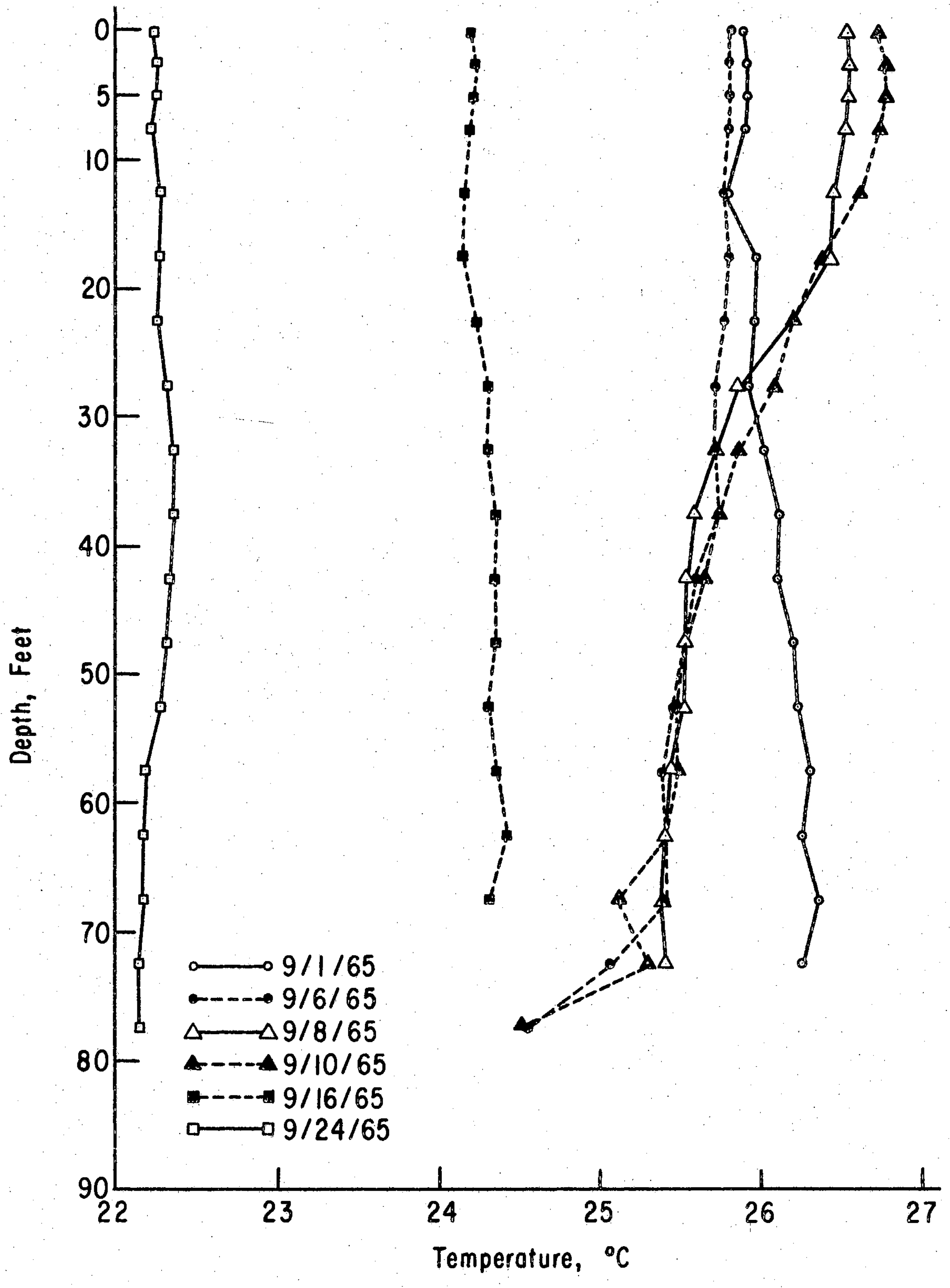

Figure 19. Lake Temperature Profiles for the September Month of the 1965 Lake Hefner Investigation.

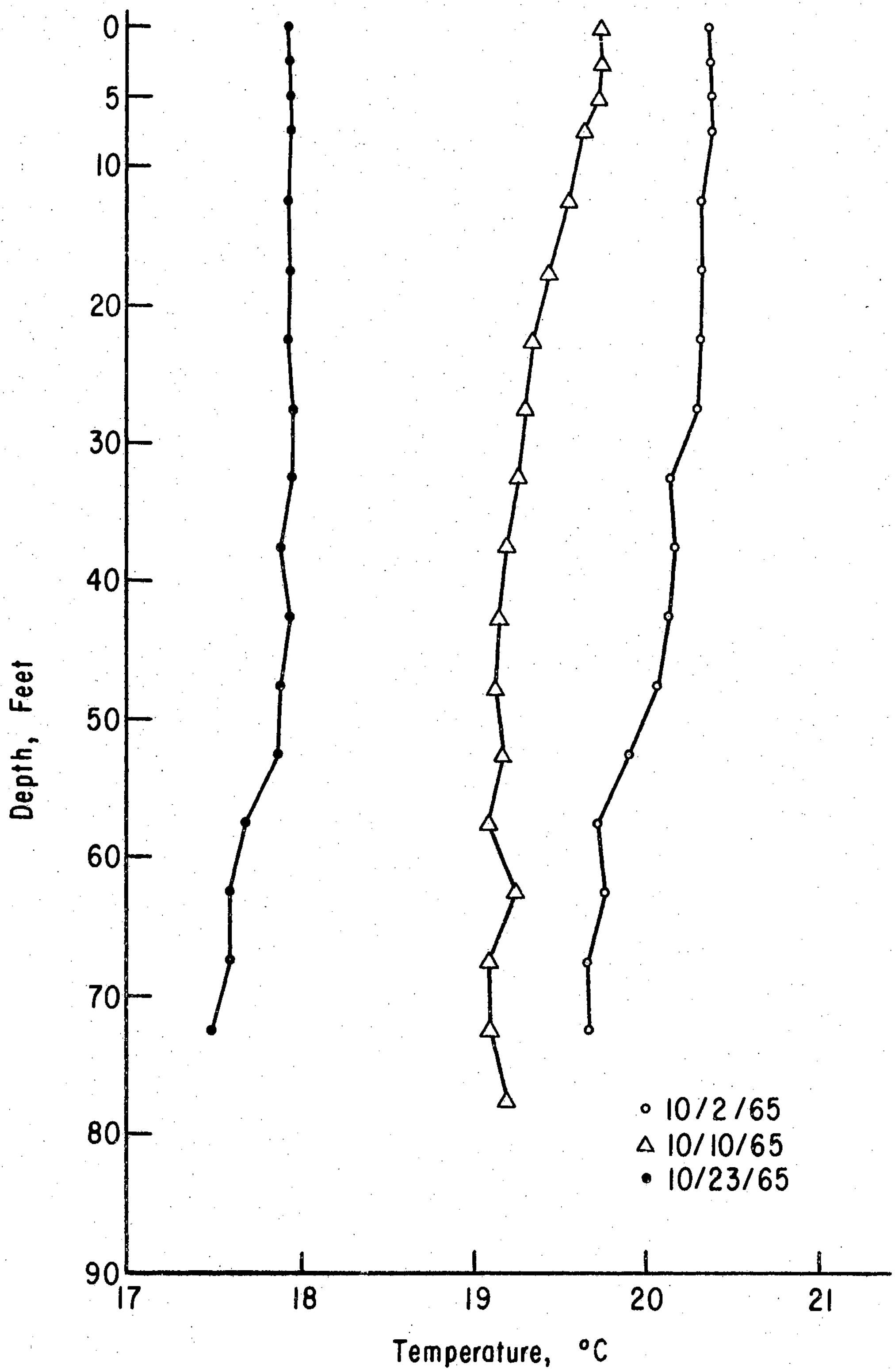

Figure 20. Lake Temperature Profiles for the October Month of the 1965 Lake Hefner Investigation.

Two other factors whose measurements were pertinent in determining the energy budget evaporation and the mass transfer coefficient were the average air temperature, T_a, and the average water surface temperature, T_o, for the thermal survey period. The variation of the factors for the study period are shown plotted in Figure 21. Peak average air temperature occurred in mid July during TSP 7. Peak average water surface temperature occurred at the same time.

Seasonal variation of the parameter, Bowen's Ratio, is shown in Figure 22. As would be expected for this study period, negative values occurred in most cases as the air temperature was usually warmer than the water surface temperature.

Mass Transfer Coefficient

These data are shown in Figures 23 and 24. The average values shown for the coefficient N were determined for the energy budget and the water budget considering all eighteen thermal survey periods. Other average values for the coefficient N were determined for the energy budget and the water budget using data from TSP 5 through TSP 13 and TSP 15 through TSP 18. The average N values for these thirteen thermal survey periods in units of centimeters per kilometer per millibar were 12.91×10^{-5} for water budget data and 15.72×10^{-5} for energy budget data.

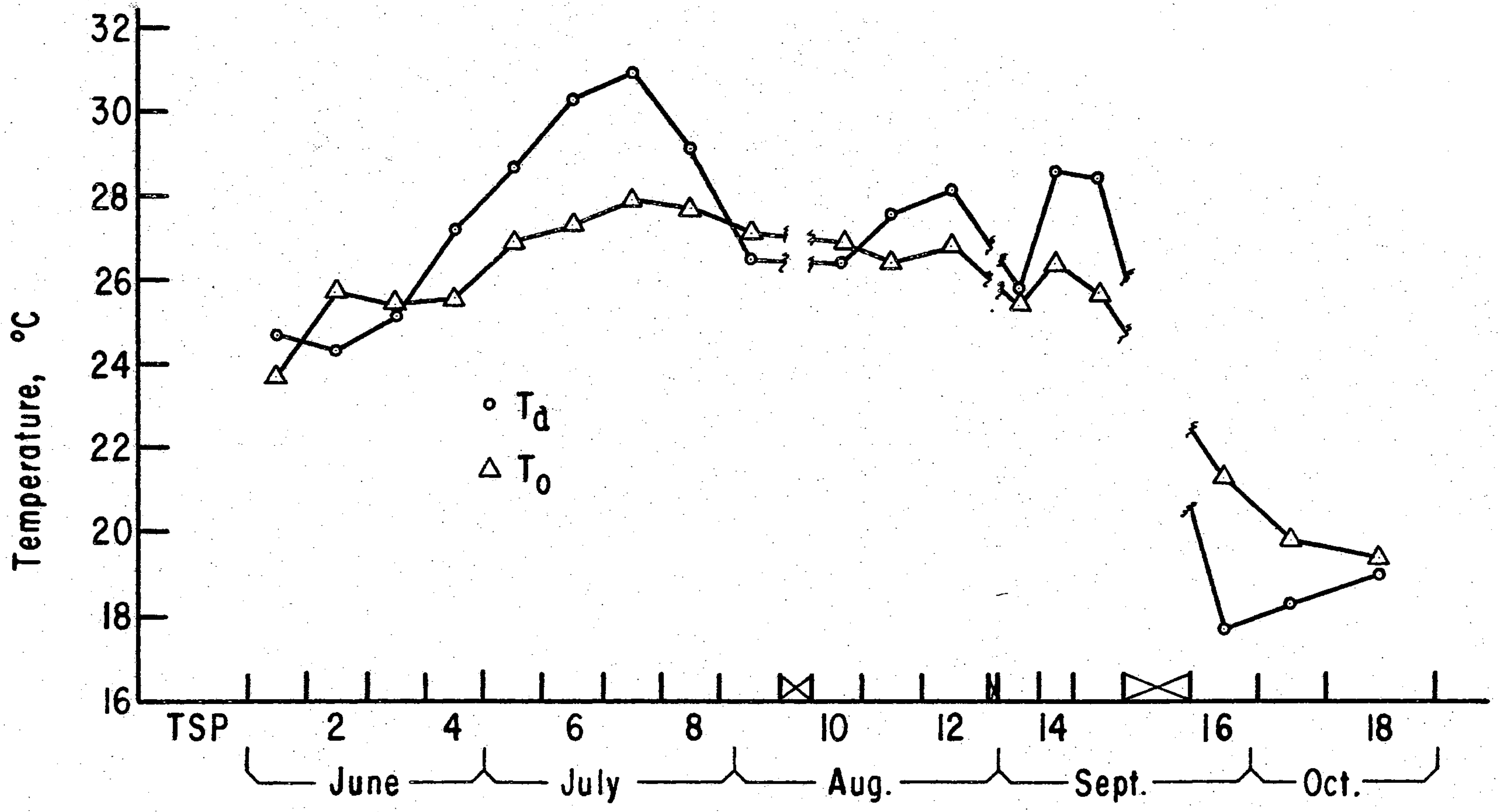

Figure 21. Variation of the Air Temperature, T_a, and the Water Surface Temperature, T_o, for the 1965 Lake Hefner Investigation Period.

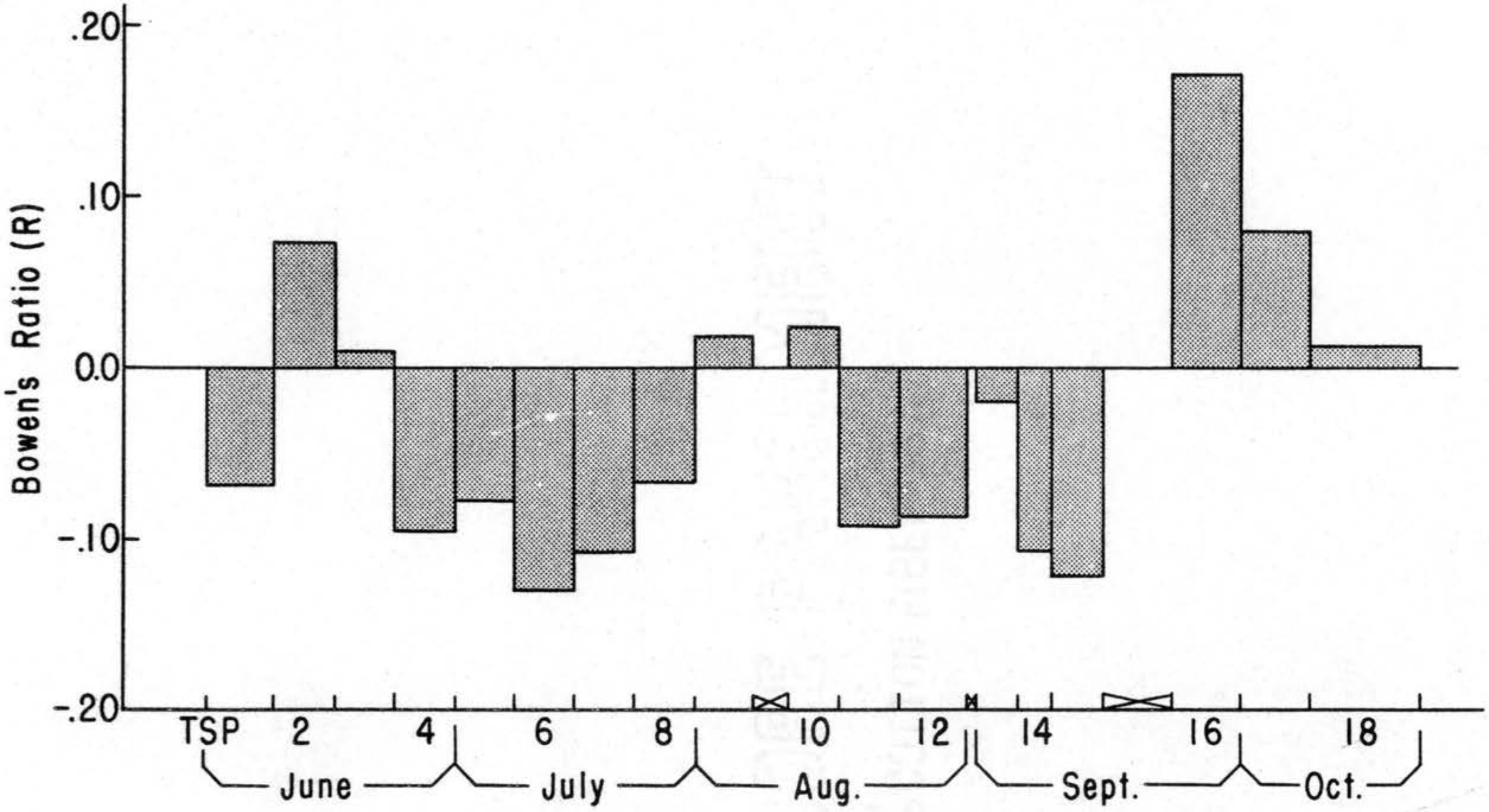

Figure 22. Bowen Ratio, R, Variation for the 1965 Lake Hefner Investigation.

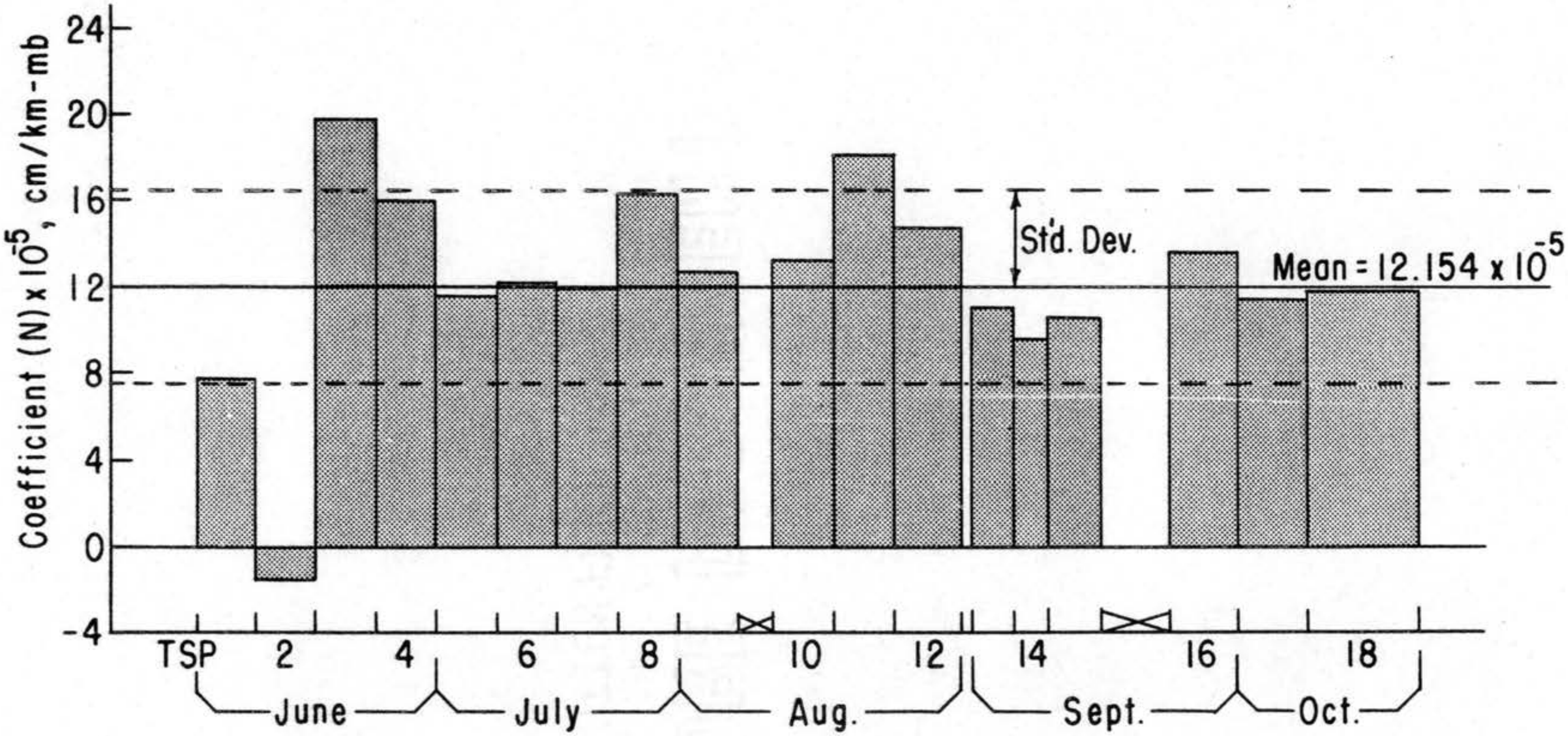

Figure 23. Mass Transfer Coefficient Variation as Determined from Water Budget Data for the 1965 Lake Hefner Investigation.

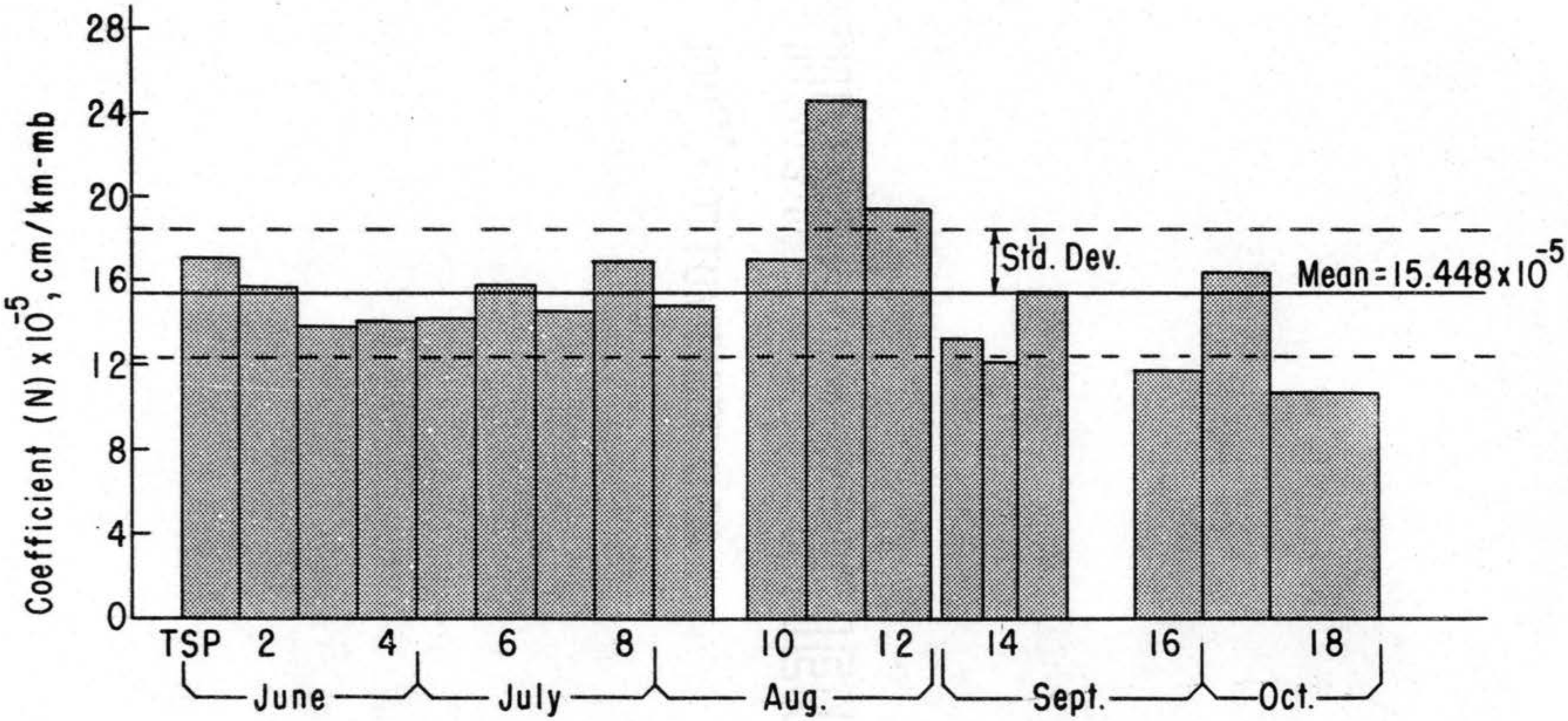

Figure 24. Mass Transfer Coefficient Variation as Determined from Energy Budget Data for the 1965 Lake Hefner Investigation.

Magnitude of N for the 1950-51 Lake Hefner study was 11.25×10^{-5} as calculated from water budget data. Comparison of the 1950-51 and 1965 average N values shows a difference of approximately 10 percent.

Assuming variances were equal, there was a significant difference in the magnitude of the mass transfer coefficient, N, between the energy budget and water budget, testing at the 95 percent level.

It was decided to test evaporation actually observed against that calculated from an average mass transfer coefficient. Evaporation rates computed by thermal survey periods using the average N values for the energy budget and water budget methods are given in Table XI. The observed evaporation rates are also listed for comparison purposes and the percent differences have been calculated. For the water budget, the largest percent difference was -27.83 for TSP 11 and the smallest percent difference was -1.83 for TSP 10. For the energy budget, the largest percent difference was 47.46 for TSP 18 and the smallest percent difference was 0.30 for TSP 6. Figures 25 and 26 show the plotted data of Table XI. A correlation coefficient, R, of 0.87 and standard deviation of 0.0914 centimeter per day were obtained comparing the observed and calculated values for the water budget. An R value of 0.85 and a standard deviation of

TABLE XI

AVERAGE EVAPORATION RATES CALCULATED WITH AVERAGE MASS TRANSFER COEFFICIENTS FROM WATER BUDGET AND ENERGY BUDGET DETERMINATIONS

	Water Budget			Energy Budget		
TSP	Calculated Evaporation Rate cm/day	Observed Evaporation Rate cm/day	Percent Difference %	Calculated Evaporation Rate cm/day	Observed Evaporation Rate cm/day	Percent Difference %
5	0.7527	0.6723	11.96	0.9170	0.8239	11.30
6	0.7710	0.7181	7.37	0.9392	0.9364	0.30
7	0.9170	0.8359	9.70	1.1171	1.0365	7.78
8	0.5509	0.6927	-20.47	0.6710	0.7181	- 6.56
9	0.8133	0.7963	2.13	0.9907	0.9327	6.22
10	0.5732	0.5839	- 1.83	0.6982	0.7564	- 7.69
11	0.3840	0.5321	-27.83	0.4678	0.7279	-35.73
12	0.5670	0.6431	-11.83	0.6907	0.8478	-18.53
13	0.7884	0.6698	17.71	0.9605	0.8048	19.35
15	1.0920	0.8809	23.96	1.3303	1.3159	1.09
16	0.7127	0.7498	- 4.95	0.8683	0.6528	33.01
17	0.3403	0.2987	13.93	0.4146	0.4315	- 3.92
18	0.5402	0.4877	10.76	0.6581	0.4463	47.46

Avg N (Water Budget) = 12.9085×10^{-5} cm/km-mb

Avg N (Energy Budget) = 15.7249×10^{-5} cm/km-mb

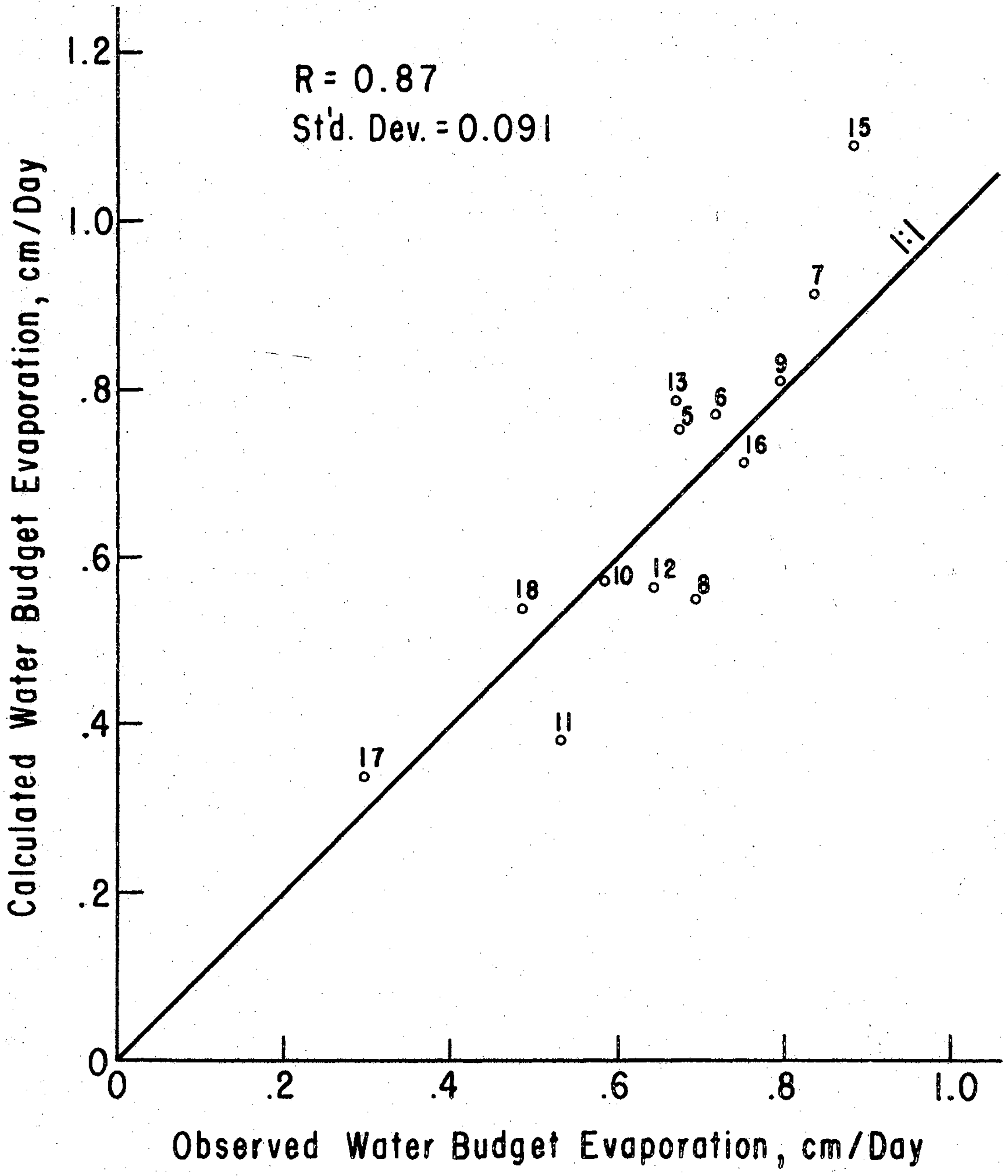

Figure 25. Comparison of the Observed Evaporation Computed by Water Budget Methods to the Calculated Evaporation from the Mass Transfer Equation Using an Average N Value of 12.91 x 10^{-5} cm/km-mb.

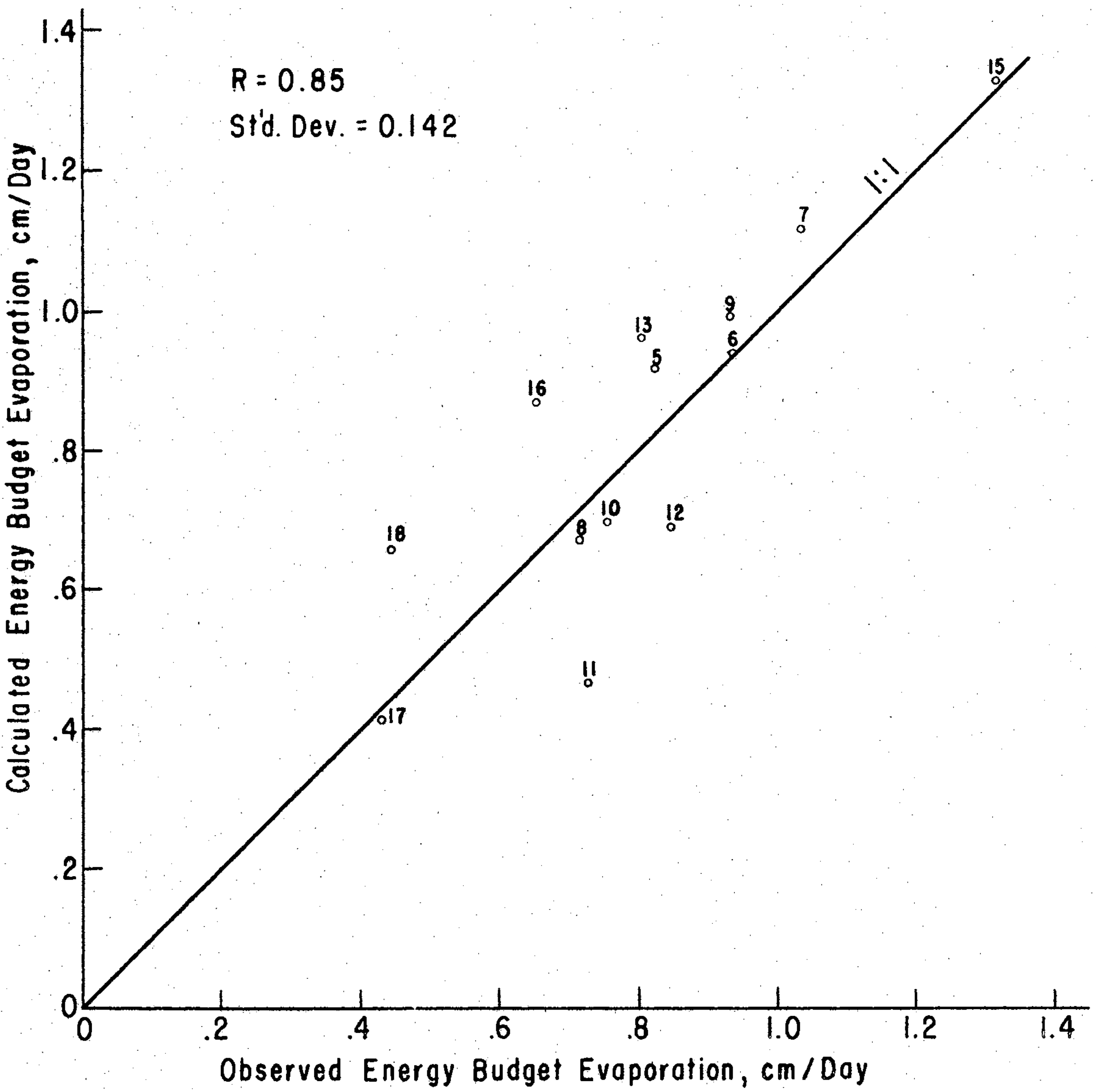

Figure 26. Comparison of the Observed Evaporation Computed by Energy Budget Methods to the Calculated Evaporation from the Mass Transfer Equation Using an Average N Value of 15.72×10^{-5} cm/km-mb.

0.1423 centimeter per day were obtained when the observed and calculated values were compared for the energy budget.

Wind

Seasonal variation of wind speed by thermal survey periods is shown in Figure 27. The average diurnal variation for the study period is shown in Figure 28.

Curve Fitting

An attempt to describe the seasonal variation of N by an equation was largely unsuccessful even excluding the values for the first four thermal survey periods and the value for TSP 14. The best correlation obtained was a fit of the energy budget data. The correlation coefficient, R, was 0.61 with a standard deviation of 2.879×10^{-5} centimeter per kilometer per millibar.

Since a good fit could not be obtained on the seasonal variation of the mass transfer coefficient, it was decided to attempt to fit a polynomial to express evaporation as a function of the several variables that were measured to compute evaporation by the mass transfer method. The equation obtained from multivariate regression of the water budget data was

$$\begin{aligned} E = {} & 4.159 - 0.09261\ T_o + 0.004695\ T_o^2 \\ & -0.2135\ T_a + 0.002942\ T_a^2 - 0.03049\ RH \\ & +0.0001904\ RH^2 + 0.0006697\ u + 0.0000007581\ u^2 \end{aligned}$$

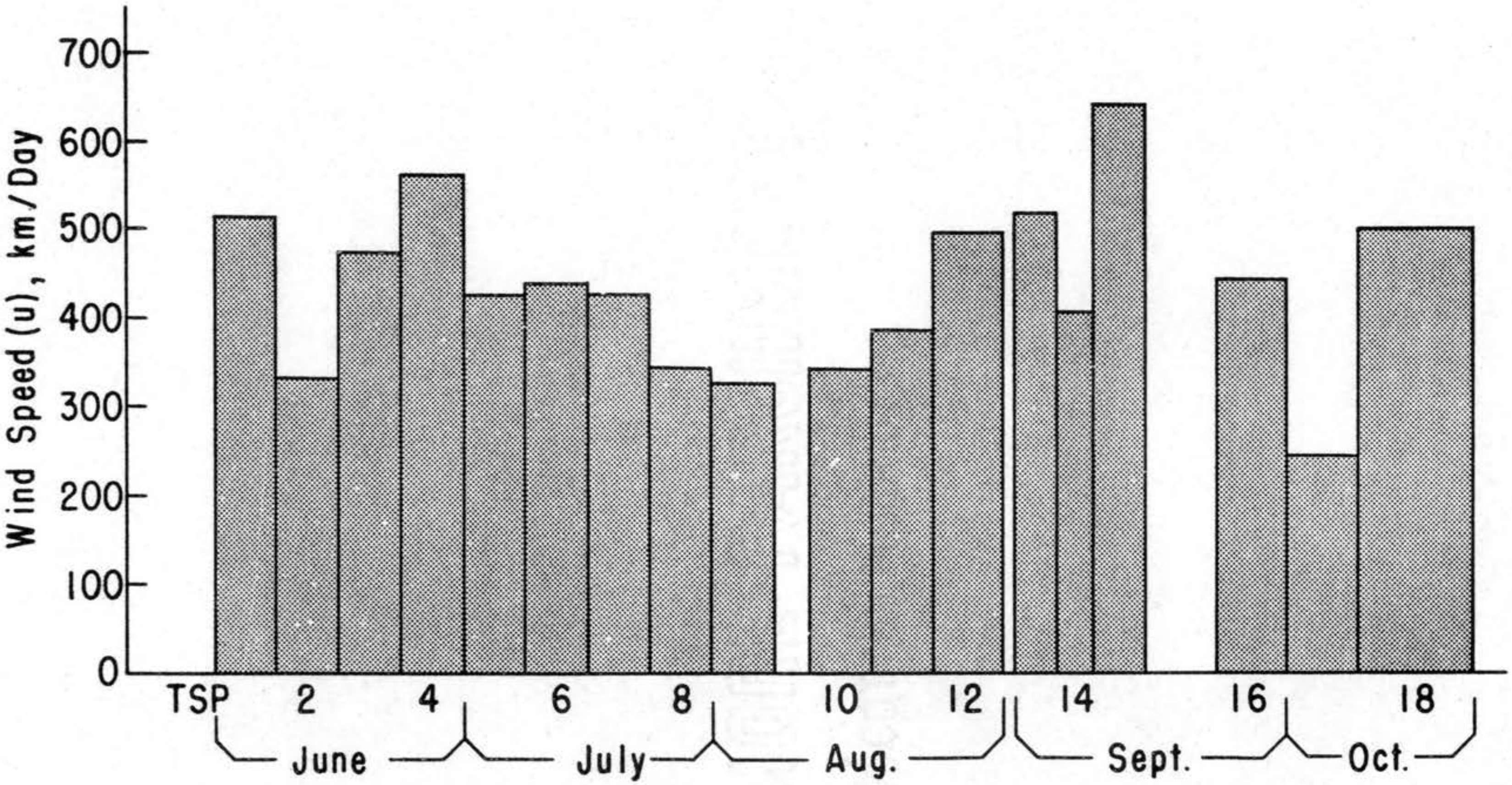

Figure 27. Wind Speed Variation at the 2-Meter Level for the South Station During the 1965 Lake Hefner Investigation Period.

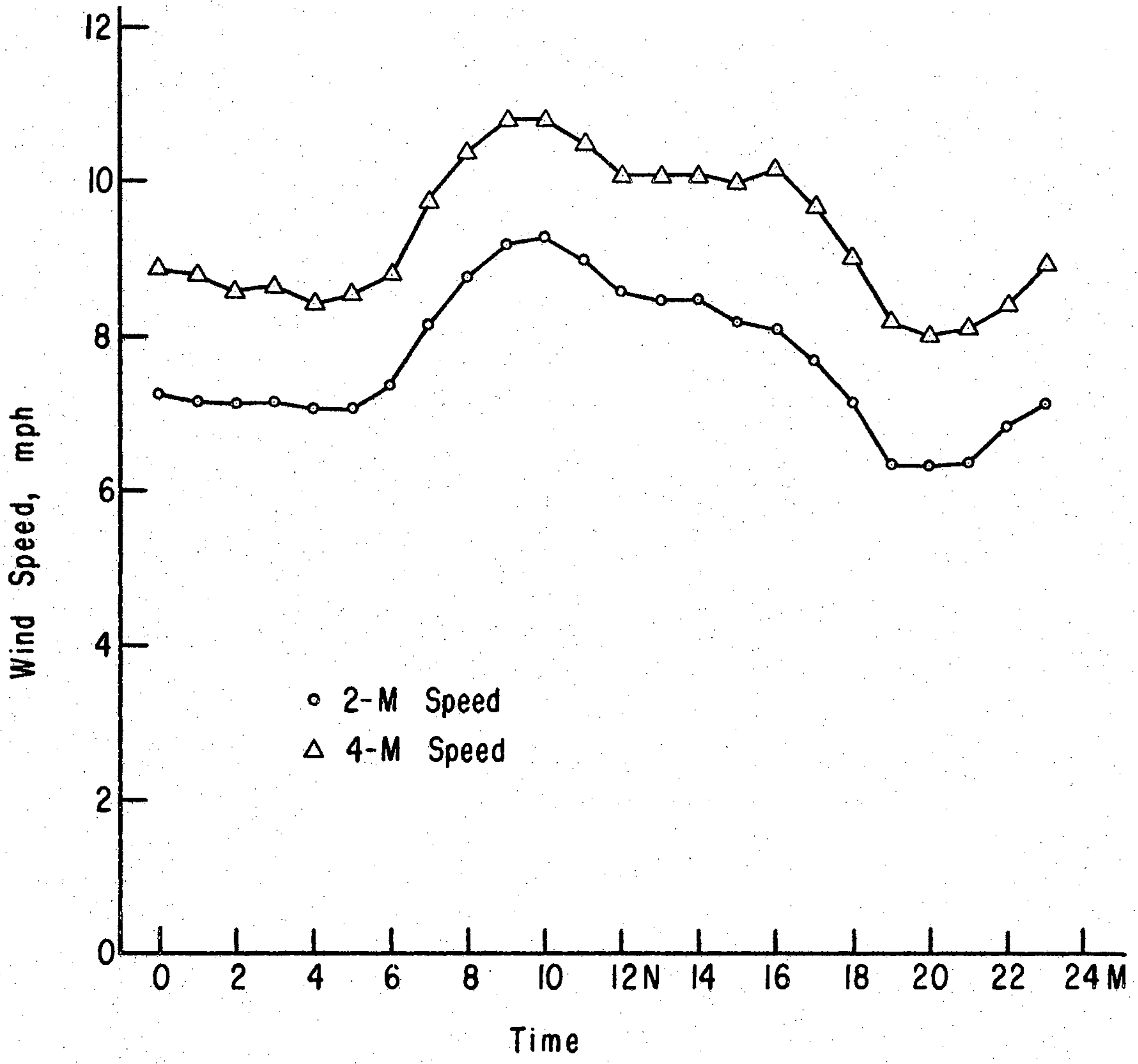

Figure 28. Average Diurnal Variation of Wind Speed at the South Station for the 1965 Lake Hefner Investigation.

where

E = evaporation rate, cm/day

T_o = average water surface temperature, °C

T_a = average air temperature, °C

RH = average relative humidity, percent

u = average wind speed, km/day

The correlation coefficient was 0.97 and the largest percent difference between a calculated value and the observed value was -7.68 for TSP 12 as shown in Table XII.

The equation obtained from the multivariate regression analysis of the energy budget data was

$$\begin{aligned} E = {} & 1.678 + 0.2900\ T_o - 0.004397\ T_o^2 \\ & -0.1426\ T_a + 0.002460\ T_a^2 - 0.09096\ RH \\ & +0.0006951\ RH^2 - 0.003477\ u + 0.000005377\ u^2 \end{aligned}$$

Correlation coefficient was 0.99 and the largest percent difference between a calculated value and the observed value was 5.95 for TSP 10 which is also shown in Table XII.

A comparison of Tables XI and XII reveals that the polynomial equation estimates evaporation in closer agreement with the observed value than estimates calculated using an average N value in the mass transfer equation. Figures 29 and 30 show the data of Table XII. These figures may be compared to Figures 25 and 26 plotted from data in Table XI.

TABLE XII

AVERAGE EVAPORATION RATES CALCULATED BY POLYNOMIAL MULTIVARIATE EQUATIONS USING TEMPERATURE, HUMIDITY AND WIND PARAMETERS

TSP	Water Budget			Energy Budget		
	Calculated Evaporation Rate	Observed Evaporation Rate	Percent Difference	Calculated Evaporation Rate	Observed Evaporation Rate	Percent Difference
	cm/day	cm/day	%	cm/day	cm/day	%
5	0.6788	0.6723	-0.97	0.8221	0.8239	0.22
6	0.7240	0.7181	-0.82	0.9059	0.9364	3.26
7	0.8537	0.8359	-2.13	1.0505	1.0365	-1.35
8	0.6399	0.6927	7.62	0.7467	0.7181	-3.99
9	0.7823	0.7963	1.75	0.9373	0.9327	-0.49
10	0.6177	0.5839	-5.78	0.7114	0.7564	5.95
11	0.4964	0.5321	6.71	0.7239	0.7279	0.56
12	0.6925	0.6431	-7.68	0.8615	0.8478	-1.61
13	0.6752	0.6698	-0.81	0.8377	0.8048	-4.09
15	0.8666	0.8809	1.62	1.3047	1.3159	0.85
16	0.7370	0.7498	1.71	0.6501	0.6528	0.41
17	0.3214	0.2987	-7.58	0.4409	0.4315	-2.17
18	0.4757	0.4877	2.45	0.4384	0.4463	1.76

Water Budget

$$E = 4.159276 - 0.092607\ T_o + 0.004695\ T_o^2 - 0.213527\ T_a + 0.002942\ T_a^2$$
$$- 0.030490\ R.H. + 0.000190\ RH^2 + 0.000670\ U + 0.000001\ U^2$$

Energy Budget

$$E = 1.678360 + 0.289969\ T_o - 0.004397\ T_o^2 - 0.142591\ T_a + 0.002460\ T_a^2$$
$$- 0.090957\ R.H. + 0.000695\ RH^2 - 0.003477\ U + 0.000005\ U^2$$

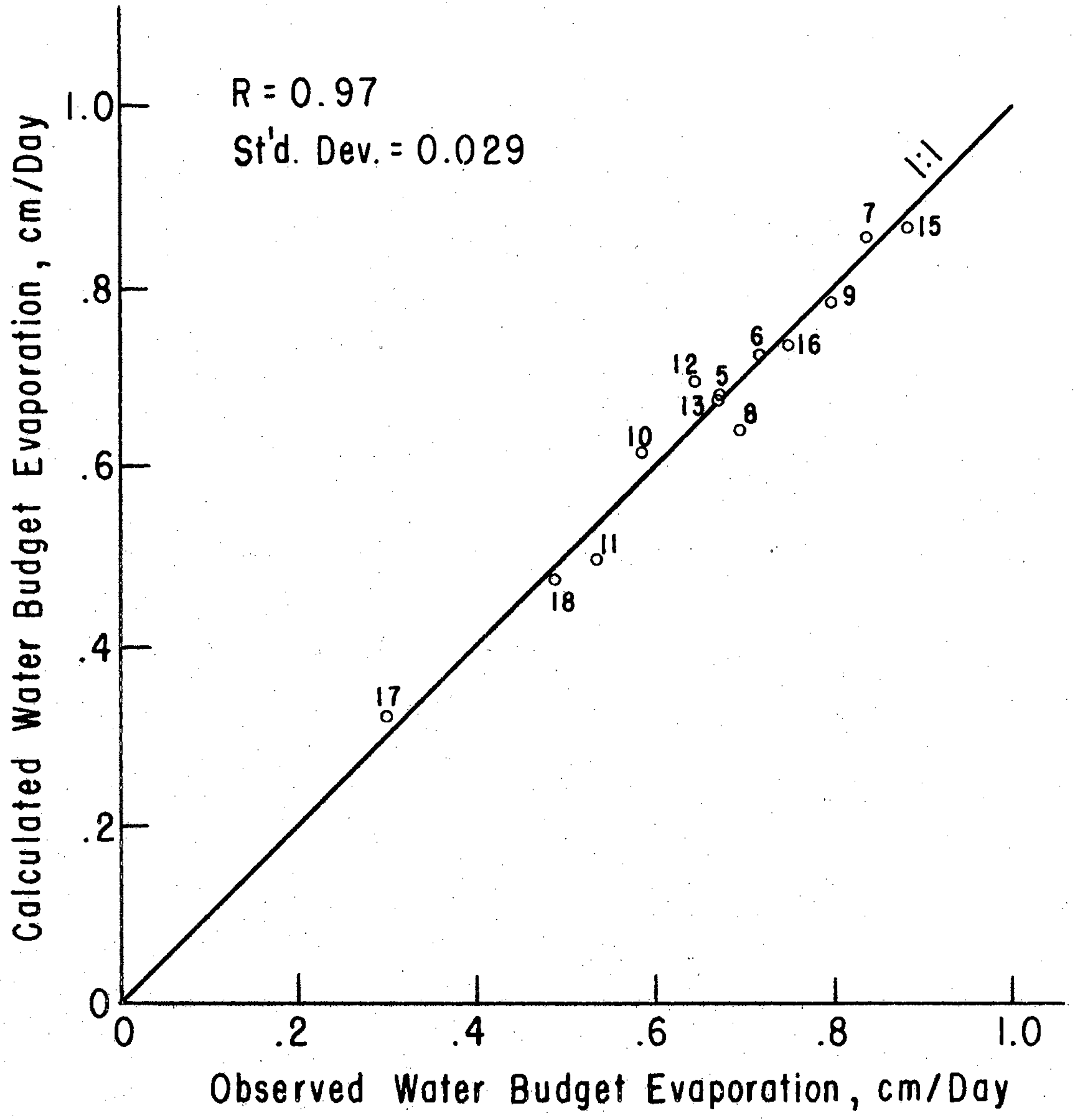

Figure 29. Average Evaporation Calculated by Polynomial Multivariate Equation Compared to the Observed Evaporation for the Water Budget.

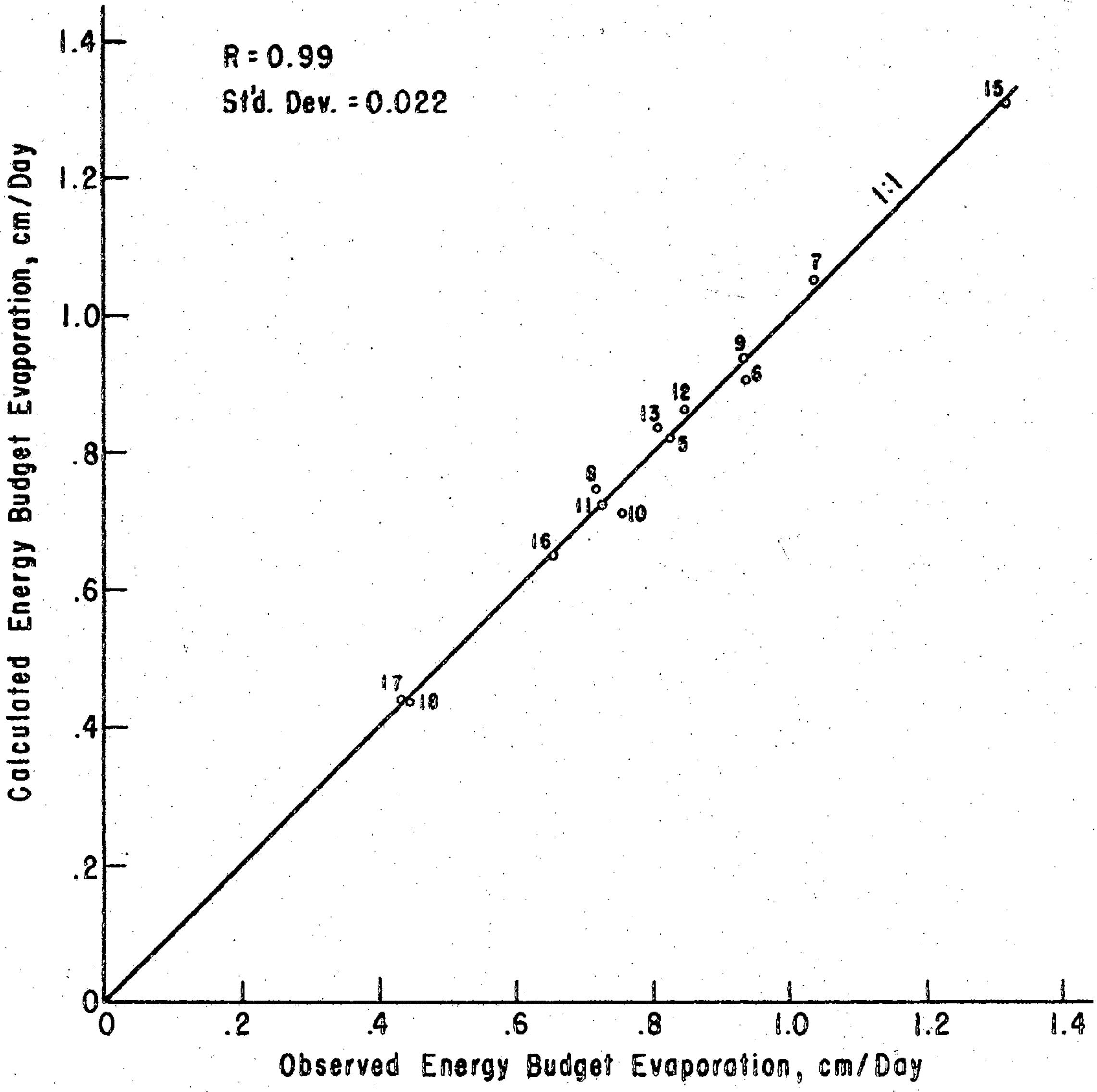

Figure 30. Average Evaporation Calculated by Polynomial Multivariate Equation Compared to the Observed Evaporation for the Energy Budget.

Completeness of Data

The percent total missing data for the period of investigation was 8.12 percent. The bulk of the missing data was caused by the faulty inking system on the water surface temperature recorder on Raft 3. Despite repeated efforts to remedy this problem there was only one thermal survey period which had complete temperature data from this raft. Considering only rafts one, two, and four, the amount lost for the rafts was 2.93 percent. For all four rafts, 13.75 percent missing data occurred. Data missing for radiation and relative humidity at the south station was 1.87 percent. Temperature data lost from the same location was 1.70 percent. There was no lost data for inflow, outflow, rainfall, and the stage measurement at the dock. Due to late installment of the stage recorder at the intake tower, 17.18 percent of the data was missed at that site.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary

The 1965 Lake Hefner evaporation study was performed as part of a series of evaporation suppression investigations conducted by the Bureau of Reclamation and cooperating agencies, including Oklahoma State University.

Objectives of this study were to determine the reservoir evaporation by water budget and energy budget methods, evaluate the mass transfer coefficient and attempt to describe the seasonal variation of the mass transfer coefficient with an equation.

Of the two methods used to determine the evaporation, the water budget method was the simplest and was considered to be the standard. The energy budget method required many of the measurements used for the water budget plus radiation and other meteorological measurements.

Results of the two methods were compared. Energy budget evaporation was higher than the water budget evaporation in fourteen out of eighteen thermal survey periods.

It was decided that the most accurate results were obtained in TSP's 5 through 13 and TSP's 15 through 18 when no large inflows occurred and no film application was made. The equation describing the relation between the energy budget evaporation and the water budget evaporation for these thermal survey periods was

$$E_{EB} = -0.0315 + 1.27\ E_{WB}$$

The average mass transfer coefficients determined for the thirteen select thermal survey periods were 12.91 x 10^{-5} centimeters per kilometer per millibar by water budget data and 15.72 x 10^{-5} centimeters per kilometer per millibar by energy budget data. The N value obtained in the 1965 Lake Hefner study was approximately 10 percent higher than the N value obtained in the 1950-51 Lake Hefner study.

There was a significant difference between the magnitudes of the N value obtained from the energy budget and the water budget when testing at the 95 percent level assuming variances equal.

Calculated evaporation using the average N values for each method were compared with the observed evaporation determined by the particular method. Correlation coefficients of 0.86 were obtained from these comparisons.

Attempts to describe the seasonal variation of the mass transfer coefficient by an equation were unsuccessful. Equations relating evaporation to the several variables normally associated with mass transfer methods were formulated for the select thirteen thermal survey periods. Results from these equations agreed well with the observed evaporation. The correlation coefficient was 0.98. The equation for the water budget was

$$E = 4.159 - 0.09261\ T_o + 0.004695\ T_o^2 - 0.2135\ T_a + 0.002942\ T_a^2 - 0.03049\ RH + 0.0001904\ RH^2 + 0.0006697\ u + 0.0000007581\ u^2$$

The equation for the energy budget was

$$E = 1.678 + 0.2900\ T_o - 0.004397\ T_o^2 - 0.1426\ T_a + 0.002460\ T_a^2 - 0.09096\ RH + 0.0006951\ RH^2 - 0.003477\ u + 0.000005377\ u^2$$

Conclusions

1. The energy budget method of computing evaporation yielded higher rates of evaporation than the water budget method.
2. The 1965 Lake Hefner mass transfer coefficient value of 12.91×10^{-5} centimeters per kilometer per millibar from water budget data of the thirteen select thermal survey periods is considered to be a reasonable value as it compares well with the 1950-51 value.
3. Insufficient data existed to find the equation that would describe the seasonal variation of the mass transfer coefficient.

4. Multivariate regression analysis may be used with some success to obtain equations capable of predicting evaporation using variables common to the mass transfer method.
5. For the range of the data obtained in this study, the polynomial equation formulated to describe evaporation as a function of temperature, humidity, and wind produced better calculated evaporation values than the mass transfer equation using the average N value from the thirteen select thermal survey periods.

Recommendations

1. It is recommended that a study be initiated to determine the minimum number of thermal survey points that need be sampled during a thermal survey to determine the representative temperature profile of the lake.
2. An attempt should be made in a future evaporation study at Lake Hefner to predict evaporation using the polynomial equations derived from the 1965 Lake Hefner data keeping in mind the range of data from which the equations were derived.

A SELECTED BIBLIOGRAPHY

1. A Water Policy for the American People, Vol. I. President's Water Resources Policy Commission. Government Printing Office, Washington, D.C. (1950).

2. Anderson, E. R., L. J. Anderson, and J. J. Marciano. "A Review of Evaporation Theory and Development of Instrumentation." Lake Mead Water Loss Investigations; Interim Report. Navy Electronics Laboratory, Report No. 159, 1950.

3. Anderson, Ernest R. "Energy-Budget Studies." Water-Loss Investigations: Lake Hefner Studies Technical Report. Geological Survey Professional Paper 269. U.S. Government Printing Office, Washington, D.C. (1954), 46-70.

4. Ångström, A. "Application of Heat Radiation Measurements to the Problem of the Evaporation from Lakes and the Heat Convection at Their Surfaces." Geografiska Annaler, Band II, 1920, 237.

5. Beard, J. Taylor and John A. Wiebelt. "The Reflectance of A Water Wave Surface as Related to the Problem of Evaporation Suppression." Paper prepared for publishing in <u>Journal of Geophysical Research</u>, (August 15, 1966).

6. Bellport, B. P. "Engineering Research on Water Storage and Transmission." Research on Water: A Symposium on Problems and Progress. ASA Special Publication No. 4 SSSA coop SCSA. Published by the SSSA. June, 1964.

7. Bigelow, F. H. "Studies of the Phenomena of Evaporation of Water Over Lakes and Reservoirs." (1907-10) U.S. Monthly Weather Review 35:311-31, illus., 1907; 36:24-39, 437-445, illus., 1908; 38:307-313, 1910.

8. Bowen, I.S. "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface." Physical Review, Vol. 27, (June, 1926), 779-787.

9. Brunt, David. Physical and Dynamical Meteorology. Cambridge at the University Press: London, (1939), 109-111.

10. Carpenter, L. G. Section of Meteorology and Irrigation Engineering. Colo. Agr. Exp. Sta. Ann. Rpt. 4: [29]-34, illus. Appendix to the report of the meteorologist and irrigation engineer. [25]-97, illus. 1891.

11. Cummings, N. W. "The Relative Importance of Wind, Humidity, and Solar Radiation in Determining Evaporation from Lakes." Physical Review Vol. 25, 1925, 721; Journal of Electricity, Vol. 46, 1925, 491.

12. Cummings, N. W. and Burt Richardson. "Evaporation from Lakes." Physical Review, Vol. 30, (October, 1927), 527-534.

13. Dalton, John. "Experimental Essays on the Constitution of Mixed Gases; on the Force of Steam or Vapor from Waters and other Liquids in Different Temperatures, both in a Torricellian Vacuum and in Air; on Evaporation; and on the Expansion of Gases by Heat." Mem. Manchester Lit. and Phil. Soc. 5: 535-602, illus. 1798.

14. Fitzgerald, Desmond. "Evaporation." Transactions of the American Society of Engineers, Vol. XV, 1886, 581.

15. Gates, D. M. Energy Exchange in the Biosphere. Harper and Row, 1962, 74.

16. Glover, R. E. Memorandum to L. O. Timblin, Jr., Head of Physical Investigations Laboratory Section. "Reduction of Energy Budget Data." Physical Investigations Laboratory Reference No. Sl-61-11. U.S. Bureau of Reclamation. Denver, Colorado, (1961).

17. Handbook of Chemistry and Physics, 13th Edition. Chemical Rubber Publishing Co. Cleveland, Ohio.

18. Harbeck. G. E., et al. "Utility of Selected Western Lakes and Reservoirs for Water Loss Studies." U.S. Geol. Survey Circ. 103. (March, 1951).

19. Harbeck G. Earl, Jr., and Frank W. Kennon. "The Water Budget Control." Water-Loss Investigations: Volume I-Lake Hefner Studies Technical Report. U.S. Geol. Survey Circ. 229, 1952.

20. Harbeck, G. Earl, Jr., and Max A. Kohler. Water-Loss Investigations: Lake Mead Studies. Geological Survey Professional Paper 298. U.S. Gov. Print. Office, Wash., D. C. (1958), 75-77.

21. Holzman, Benjamin. "The Heat Balance Method for the Determination of Evaporation from Water Surfaces." Trans. American Geophysical Union, Vol. 22, Part III, 1941, 655-59.

22. Koberg. G. E. "Methods to Compute Long-Wave Radiation from the Atmosphere and Reflected Solar Radiation from a Water Surface." United States Geological Survey Professional Paper 272-F, United States Government Printing Office, Washington. (1964).

23. Langbein, W. B., C. H. Hains, and R. C. Culler. "Hydrology of Stock-Water Reservoirs in Arizona." U.S. Geol. Survey Circ. 110, 1951.

24. Linsley, Ray K., Jr., Max A. Kohler, and Joseph L. Paulhus. Hydrology for Engineers. New York: McGraw-Hill Book Company, Inc., 1958, 98.

25. Marciano, J. J. and G. Earl Harbeck, Jr. "Mass-Transfer Studies." Water-Loss Investigations: Lake Hefner Studies Technical Report. Geological Survey Professional Paper 269. U.S. Gov. Print. Office, Wash., D.C. (1954), 46-70.

26. Meyer, J. Stuart and Tor J. Nordenson. "Evaporation from the 17 Western States." Geological Survey Professional Paper No. 272-D. United States Government Printing Office, Washington:1962.

27. Powell, W. M., and G. L. Clarke. "The Reflection and Absorption of Daylight at the Surface of the Ocean." Optical Society of America Journal, Vol. 26, No. 3. (March, 1936), 111-120.

28. Richardson, Burt, Esq. "Evaporation as a Function of Insolation." Transactions American Soc. of Civil Engineers, Vol. 95, 1931, 996-1019.

29. Rohwer, Carl. Evaporation from Free Water Surfaces. U.S. Dept. of Agriculture Tech. Bull. 271, 1931.

30. Schmidt, W. "Strahlung und Verdunstung in Freien Masserflachen; ein Beitrage zum Warmehaushalt des Weltmeers und zum Wasserhaushalt der Erde." Annalen der Hydrographic und Maritmen Meteorologic, Vol. 43, 1915, 111-124, 169-178.

31. Smithsonian Meteorological Tables, Sixth Revised Edition, Smithsonian Miscellaneous Collections, Volume 114. Published by the Smithsonian Institution, Washington, D.C. (1951).

32. Sverdrup, H. U. "On the Annual and Diurnal Variation of the Evaporation from the Oceans." Journal of Marine Research, Vol. 3, No. 2, 1940.

APPENDIX A

TABLE A-I

CALCULATION OF AMSLER INTEGRATOR CONSTANTS FOR FLAT-PLATE TEMPERATURE HONEYWELL CHART NO. 5229 REFERENCE LINE AT 50° F

TEMP	TEMP	BLACK-BODY RADIATION	BLACK-BODY RADIATION FOR 60 HRS	DIFFERENCE FROM 50°F
°F	°K	cal/cm^2-min	cal/cm^2	cal/cm^2
50	283.16	0.5228	1882.080	
70	294.27	0.6098	2195.280	313.200
90	305.38	0.7072	2545.920	663.840
110	316.49	0.8159	2937.240	1055.160

$$c_1\ 85.668 + c_2\ 62.987 + c_3\ 54.685 = 313.200$$

$$c_1\ 174.488 + c_2\ 257.198 + c_3\ 491.120 = 663.840$$

$$c_1\ 265.404 + c_2\ 591.187 + c_3\ 1727.913 = 1055.160$$

The solutions of the above simultaneous equations were found to be:

$c_0 = 0.5228$ cal/cm^2-min

$c_1 = 3.5285$ cal/cm^2-in^2

$c_2 = 0.1618$ cal/cm^2-in^3

$c_3 = 0.0133$ cal/cm^2-in^4

TABLE A-II

CALCULATION OF AMSLER INTERGRATOR CONSTANTS FOR FLAT PLATE TEMPERATURE - WESTON ELECTRIC INST. CORP. - CHART NO. 240882 - REFERENCE LINE AT 55.1 °F*

TEMP	MILIVOLT OUTPUT	TEMP	BLACK-BODY RADIATION	BLACK-BODY RADIATION FOR 60 HRS	DIFFERENCE FROM 55.1°F
°F		°K	cal/cm^2-hr	cal/cm^2	cal/cm^2
55.1	0.5000	286.0	32.642	1958.52	
75.1	0.9450	297.1	38.018	2281.80	322.56
95.1	1.4020	308.2	44.032	2641.92	683.40
115.1	1.8705	319.3	50.716	3042.96	1084.44

$$c_1\ 88.998 + c_2\ 66.005 + c_3\ 65.271 = 322.56$$

$$c_1\ 180.402 + c_2\ 271.207 + c_3\ 543.626 = 683.40$$

$$c_1\ 274.098 + c_2\ 626.081 + c_3 1906.750 = 1084.44$$

The solutions of the above simultaneous equations were found to be:

$c_0 = 0.5440$ cal/cm^2-min

$c_1 = 3.4650$ cal/cm^2-in^2

$c_2 = 0.2147$ cal/cm^2-in^3

$c_3 = 0.00014$ cal/cm^2-in^4

---

*Reference line is equivalent to chart line of 100.

APPENDIX B

TABLE B-I

CALCULATION OF THE INCOMING SOLAR RADIATION FOR THERMAL SURVEY PERIOD NUMBER EIGHT

TSP	DATE	TIME	① TIME INTERVAL hrs	② ENERGY BELOW RL ①×60×0.5 cal/cm^2	③ AREA UNDER CURVE in^2	④ RADIATION ABOVE RL ③x16.338 cal/cm^2	⑤ TOTAL RADIATION ②+④ cal/cm^2	⑥ DRIFT CORR cal/cm^2	⑦ ADJUSTED RADIATION ⑤+⑥ cal/cm^2	⑧ AMBIENT TEMP CORR	⑨ SOLAR RADIATION ⑦×⑧ cal/cm^2
	22 July	0830									
			60.0	1800.0	- 7.486	- 122.306	1677.694	34.560	1712.254	1.0547	1805.914
	24 July	2030									
8			60.0	1800.0	-64.043	-1046.335	753.665	34.560	788.225	1.0471	825.350
	27 July	0830									
			47.5	1425.0	-34.155	- 558.024	866.976	27.360	894.336	1.0460	935.475
	29 July	0800									
										Total =	3566.739

RL = Reference Line

1 in^2 = 16.338 cal/cm^2 (South Station)

Energy Below RL = (Time Interval)(60)(RL = 0.50)

Drift Correction =(Time Interval)(60)(Drift)

TABLE B-II

CALCULATION OF THE RECORDED COMPONENT OF TOTAL INCOMING RADIATION FOR THERMAL SURVEY PERIOD NUMBER EIGHT

TSP	DATE	TIME	① TIME INTERVAL hrs	② ENERGY BELOW RL ①×60×0.5 cal/cm^2	③ AREA UNDER CURVE in^2	④ RADIATION ABOVE RL ③x16.338 cal/cm^2	⑤ TOTAL RADIATION ②+④ cal/cm^2	⑥ DRIFT CORR cal/cm^2	⑦ ADJUSTED RADIATION ⑤+⑥ cal/cm^2	⑧ PLATE TEMP CORR	⑨ RECORDED RADIATION ⑦×⑧ cal/cm^2
	22 July	0830									
			60.0	1800.0	-15.299	- 249.955	1550.045	34.560	1584.605	0.980	1552.913
	24 July	2030									
8			60.0	1800.0	-74.343	-1214.616	585.384	34.560	619.944	0.995	616.844
	27 July	0830									
			47.5	1425.0	-41.968	- 685.673	739.327	27.360	766.687	0.997	764.387
	29 July	0800									
											Total = 2934.144

RL = Reference Line

1 in^2 = 16.338 cal/cm^2 (South Station)

Energy Below RL = (Time Interval)(60)(RL = 0.50)

Drift Correction = (Time Interval)(60)(Drift)

TABLE B-III

CALCULATION OF BACK RADIATION FROM THE RADIOMETER PLATE FOR THERMAL SURVEY PERIOD NUMBER EIGHT

TSP	DATE	TIME	TIME INTERVAL	A	M	J	$C_o t$	$C_1 A$	$C_2 M$	$C_3 J$	BACK RADIATION
			hrs	in^2	in^3	in^4	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
	22 July	0830									
			60.0	195.401	336.361	814.95	1882.04	689.472	54.423	10.84	2636.78
	24 July	2030									
8			60.0	145.817	187.949	335.52	1882.04	514.515	30.410	4.46	2431.42
	27 July	0830									
			47.5	110.648	148.696	292.25	1489.95	390.421	24.059	3.89	1908.32
	29 July	0800									
										Total =	6976.52

t = (Time Interval) (60 min/hr)

C_o = 0.5228 cal/cm^2-min

C_1 = 3.5285 cal/cm^2-in^2

C_2 = 0.1618 cal/cm^2-in^3

C_3 = 0.0133 cal/cm^2-in^4

TABLE B-IV

CALCULATION OF BACK RADIANT ENERGY FROM THE WATER SURFACE FOR THERMAL SURVEY PERIOD NUMBER EIGHT

TSP	DATE	TIME	AVG RAFT TEMP °F	BACK RADIATION $Q_{bs}=(0.97)\sigma(T)^4$ cal/cm²-hr	TIME INTERVAL hrs	TOTAL DAILY BACK RADIATION cal/cm²-day
8	22 July	0830	80.9	38.50312	15.5	596.8
	23		81.3	38.61720	24.0	926.8
	24		82.1	38.84614	24.0	932.3
	25		82.4	38.93225	24.0	934.4
	26		81.7	38.73154	24.0	929.6
	27		82.8	39.04729	24.0	937.1
	28		81.9	38.78881	24.0	930.9
	29 July	0800	81.1	38.56013	8.0	308.5
					Total =	6496.4

Stefan Boltzmann Constant (σ) = 8.132×10^{-11} cal/cm^2-min-°K^4

TABLE B-V

CALCULATION OF INTERNAL ENERGY OF PRECIPITATION DURING THERMAL SURVEY PERIOD NUMBER EIGHT

DATE	TIME	① AVG AMOUNT	② SURFACE AREA	③ VOLUME 2.54 ①×②	④ TEMP	⑤ ρC_p	⑥ ENERGY ③×④×⑤
		in	cm^{2}x10^{10}	cm^{3}x10^{10}	$^\circ$C	cal/cm^3 $^\circ$C	cal
24 July	1530	0.050	10.16950	1.2915	24.44	0.9984	31.5137
25 July	1450	0.580	10.16610	14.9767	20.84	0.9988	311.7399
27 July	1915	0.950	10.16578	24.5300	20.98	0.9986	513.9187
28 July	1407	0.063	10.16473	1.6266	22.50	0.9985	36.5436
						Total =	893.7159

TABLE B-VI

CALCULATION OF INTERNAL ENERGY OF SURFACE INFLOW FOR THERMAL SURVEY PERIOD NUMBER EIGHT

DATE	TIME	① INFLOW VOLUME	② INFLOW VOLUME ①× 1.23349 $x10^9cm^3$	③ TEMP	④ TEMP	⑤ VOLUME-TEMP PRODUCT ②×④
		acre-ft	cm^3x10^9	°F	°C	cm^3-°Cx10^9
22 July	0830					
		0.257	0.316	84.2	29.0	9.164
22 July	2400					
		0.397	0.490	83.0	28.3	13.867
23 July	2400					
		0.198	0.244	82.7	28.2	6.881
24 July	2400					
				No Inflow		
25 July	2400					
				No Inflow		
26 July	2400					
		0.397	0.490	82.7	28.2	13.818
27 July	2400					
		0.793	0.978	81.2	27.3	26.699
28 July	2400					
		0.132	0.163	79.1	26.2	4.271
29 July	0800					

Total = 74.709 cm^3-°C

ρC_p x Total = 74.550x10^9cal

ρC_p = 0.998 cal/cm^3-°C

TABLE B-VII

CALCULATION OF INTERNAL ENERGY OF WATER PLANT WITHDRAWALS FOR THERMAL SURVEY NUMBER EIGHT

DATE	TIME	① OUTFLOW VOLUME	② OUTFLOW VOLUME ①×3785.41 x10^{6}cm^3	③ TEMP	④ TEMP	⑤ VOLUME-TEMP PRODUCT ②×④
		mgd	cm^{3}x10^9	$^\circ$F	$^\circ$C	cm^3-$^\circ$Cx10^9
22 July	0830					
		19.316	73.1190	81	27.2	1989
22 July	2400					
		30.330	114.8115	81	27.2	3123
23 July	2400					
		24.100	91.2284	81	27.2	2481
24 July	2400					
		13.840	52.3901	81	27.2	1425
25 July	2400					
		16.550	62.6485	81	27.2	1704
26 July	2400					
		15.830	59.9230	81	27.2	1630
27 July	2400					
		4.110	15.5580	81	27.2	423
28 July	2400					
		0.270	1.0221	80	26.7	27.3
29 July	2400					

Total = 12802.3cm^3-°C

ρC_p x Total = 12776.7x10^{9}cal

ρC_p = .998 cal/cm^3-°C

TABLE B-VIII

COMPUTED INTERNAL ENERGY OF RESERVOIR FOR JULY 22, 1965

Stage ft	Temp °C	Surface Area acres
1198.39	26.92	2519.64
1195.89	26.95	2401.04
1193.39	26.94	2281.76
1190.89	26.92	2162.11
1185.89	26.91	1908.62
1180.89	26.87	1652.88
1175.89	26.87	1413.96
1170.89	26.82	1199.65
1165.89	26.74	993.44
1160.89	26.55	806.28
1155.89	26.29	634.25
1150.89	26.11	499.84
1145.89	25.92	375.24
1140.89	25.78	275.12
1135.89	25.78	204.75
1130.89	25.64	108.60
1125.89	25.07	64.37
1120.89	25.40	35.56
1115.89	24.35	11.17

```
WEIGHTED AVERAGE TEMP =   26.78  DEGREES CENT

STORAGE ENERGY =  0.2436344E 16  CALORIES
```

TABLE B-IX

COMPUTED INTERNAL ENERGY OF RESERVOIR FOR JULY 29, 1965

Stage ft	Temp °C	Surface Area acres
1198.21	27.05	2511.10
1195.71	27.10	2392.50
1193.21	27.12	2273.15
1190.71	27.12	2153.50
1185.71	27.11	1899.39
1180.71	27.10	1643.68
1175.71	27.04	1405.49
1170.71	26.99	1192.10
1165.71	26.90	986.05
1160.71	26.76	799.68
1155.71	26.56	628.15
1150.71	26.33	495.28
1145.71	26.09	370.77
1140.71	25.94	271.70
1135.71	25.82	202.41
1130.71	25.54	104.90

WEIGHTED AVERAGE TEMP = 26.97 DEGREES CENT

STORAGE ENERGY = 0.2446784E 16 CALORIES

TABLE B-X

THERMAL SURVEY PERIOD EIGHT EVAPORATION DETERMINED FROM WATER BUDGET DATA

DATE	TIME	SURFACE AREA	LAKE STAGE	STAGE CHANGE	WATER PLANT WITHDRAWAL	IRRIGATION	SEEPAGE	INFLOW	RAIN	THERMAL EXPANSION	EVAP	EVAP	
		acres	ft	ft	ft	ft	ft	ft	ft	ft	ft	in	
JULY 22	0830	2519.69	1198.360	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	0.0000	BEG TSP 8
JULY 22	2400	2517.32	1198.344	-0.0430	0.0235	0.0004	0.0003	0.0001	0.0000	0.0002	0.0191	0.2292	
JULY 23	2400	2514.47	1198.275	-0.0690	0.0370	0.0006	0.0003	0.0002	0.0000	0.0002	0.0315	0.3780	
JULY 24	2400	2512.10	1198.226	-0.0490	0.0294	0.0006	0.0003	0.0001	0.0031	0.0002	0.0221	0.2652	
JULY 25	2400	2512.10	1198.233	0.0070	0.0169	0.0006	0.0004	0.0000	0.0442	0.0001	0.0194	0.2328	
JULY 26	2400	2510.68	1198.200	-0.0330	0.0202	0.0006	0.0005	0.0000	0.0000	0.0002	0.0119	0.1428	
JULY 27	2400	2512.10	1198.209	0.0090	0.0193	0.0006	0.0004	0.0002	0.0453	0.0002	0.0164	0.1968	
JULY 28	2400	2511.63	1198.219	0.0100	0.0050	0.0006	0.0006	0.0003	0.0453	0.0002	0.0296	0.3552	
JULY 29	0800	2511.15	1198.210	-0.0090	0.0003	0.0002	0.0002	0.0001	0.0000	0.0002	0.0086	0.1032	END TSP 8
TOTALS				-0.1770	0.1516	0.0042	0.0030	0.0010	0.1379	0.0015	0.1586	1.9032	
AVERAGES FOR TSP											0.0227	0.2727	

APPENDIX C

TABLE C-I

PROGRAM FOR INTERNAL ENERGY OF RESERVOIR

```
$JOB   WATFOR     BILL NOLEN                      7311-50001
C      LAKE HEFNER STORAGE ENERGY
C      PROGRAMMER - FRY
C      AREA DETERMINATION EQUATIONS COMPUTED FROM STAGE-CAPACITY TABLE DA
C     1TA FOR FIVE FOOT INCREMENTS
C      THERMAL SURVEY LOCATIONS EQUAL THIRTY-ONE
C      STAGE 1110.00 BOTTOM OF LAKE AND AREA IS ASSUMED EQUAL TO ZERO
C      K EQUALS NUMBER OF DEPTHS SAMPLED AT DEEPEST THERMAL SURVEY POINT
C      DEPTH IS DEPTH AT SAMPLING STAGE
C      NOL EQUALS NUMBER OF LOCATIONS SAMPLED AT A PARTICULAR DEPTH
C      ZERO IS ASSIGNED TO LOCATIONS WHERE NO TEMPERATURE DATA EXIST
C      NTPD COUNTS CORRECTIONS AT A PARTICULAR DEPTH OR STAGE
C      N IS A COUNTER
C      WAVTP IS A WEIGHTED AVERAGE TEMPERATURE OF THE RESERVOIR
       DIMENSION A(150),AT(25),STAGE(25),AREA(25),ATA(25),TEMPU(32)
     1 FORMAT(I2,5X,F8.3,2X,2A4)
     2 FORMAT(F4.1,2X,I2)
     3 FORMAT(F4.1)
     4 FORMAT(1H0,47X,5HSTAGE,10X,12HAVERAGE TEMP,10X,4HAREA/)
     5 FORMAT(1H ,43X,F10.2,9X,F8.2,9X,F10.2)
     6 FORMAT(1H0,46X,17HSTORAGE ENERGY = ,E14.8,2X,8HCALORIES)
   350 FORMAT(1H1,63X,2A4/)
  400  FORMAT(35X,F5.2)
   410 FORMAT(1H0,46X,23HWEIGHTED AVERAGE TEMP =,F8.2,2X,18HDEGREES CENTI
     1GRADE)
  935  FORMAT(1H1)
     8 N = 0
     9 READ(5,1)K,ELEV,R,S
       WRITE(6,350)R,S
     7 WRITE(6,4)
    10 TOTEMP = 0.0
    12 NTPD = 0
    15 READ(5,2)DEPTH,NOL
    18 READ(5,400)(TEMPU(I),I=1,NOL)
    20 DO 60 L=1,NOL
    25 TEMPUC = TEMPU(L)
    30 IF (TEMPUC.EQ.0.0)GO TO 60
    35 IF (TEMPUC.LT.20.)GO TO 45
    37 IF (TEMPUC.LT.25.)GO TO 50
    39 IF (TEMPUC.LT.30.)GO TO 55
    40 TEMPC  = (TEMPUC+0.61887500)/1.0127225
    43 GO TO 57
    45 TEMPC  = (TEMPUC+1.0879500)/1.0628170
    48 GO TO 57
    50 TEMPC  = (TEMPUC+1.8318514)/1.0814674
    53 GO TO 57
    55 TEMPC  = (TEMPUC+1.3504520)/1.0454775
    57 NTPD = NTPD+1
    58 TOTEMP = TOTEMP+TEMPC
    60 CONTINUE
    62 N = N+1
    64 STAGE(N) = ELEV-DEPTH
    66 AT(N) = TOTEMP/FLOAT(NTPD)
       FAKE = AT(N)*100.
       NFAKE = FAKE
       IF ((FAKE-(FLOAT(NFAKE)/100.))-0.005)500,510,520
   500 AT(N) = FLOAT(NFAKE)/100.
       GO TO 70
   510 IF (2*(NFAKE/2).EQ.NFAKE)GO TO 500
   520 AT(N) = FLOAT(NFAKE)/100.+0.01
    70 IF (STAGE(N).LT.1115.)GO TO 175
    71 IF (STAGE(N).LT.1120.)GO TO 170
    72 IF (STAGE(N).LT.1125.)GO TO 165
```

TABLE C-I (Continued)

```
 73 IF (STAGE(N).LT.1130.)GO TO 160
 74 IF (STAGE(N).LT.1135.)GO TO 155
 75 IF (STAGE(N).LT.1140.)GO TO 150
 76 IF (STAGE(N).LT.1145.)GO TO 145
 77 IF (STAGE(N).LT.1150.)GO TO 140
 78 IF (STAGE(N).LT.1155.)GO TO 135
 79 IF (STAGE(N).LT.1160.)GO TO 130
 80 IF (STAGE(N).LT.1165.)GO TO 125
 81 IF (STAGE(N).LT.1170.)GO TO 120
 82 IF (STAGE(N).LT.1175.)GO TO 115
 83 IF (STAGE(N).LT.1180.)GO TO 110
 84 IF (STAGE(N).LT.1185.)GO TO 105
 85 IF (STAGE(N).LT.1190.)GO TO 100
 86 IF (STAGE(N).LT.1195.)GO TO  95
 90 AREA(N) = 47.440*STAGE(N)-54331.99
 91 GO TO 200
 95 AREA(N) = 47.860*STAGE(N)-54833.89
 96 GO TO 200
100 AREA(N) = 51.312*STAGE(N)-58941.77
101 GO TO 200
105 AREA(N) = 51.112*STAGE(N)-58704.77
106 GO TO 200
110 AREA(N) = 47.064*STAGE(N)-53928.13
111 GO TO 200
115 AREA(N) = 41.952*STAGE(N)-47921.53
116 GO TO 200
120 AREA(N) = 41.088*STAGE(N)-46910.65
121 GO TO 200
125 AREA(N) = 36.642*STAGE(N)-41731.06
126 GO TO 200
130 AREA(N) = 33.920*STAGE(N)-38573.54
131 GO TO 200
135 AREA(N) = 25.358*STAGE(N)-28684.43
136 GO TO 200
140 AREA(N) = 24.826*STAGE(N)-28072.63
141 GO TO 200
145 AREA(N) = 18.984*STAGE(N)-21383.54
146 GO TO 200
150 AREA(N) = 13.010*STAGE(N)-14573.18
151 GO TO 200
155 AREA(N) = 20.578*STAGE(N)-23162.86
156 GO TO 200
160 AREA(N) = 6.306*STAGE(N)-7035.50
161 GO TO 200
165 AREA(N) = 5.644*STAGE(N)-6290.75
166 GO TO 200
170 AREA(N) = 4.712*STAGE(N)-5246.91
171 GO TO 200
175 AREA(N) = 1.262*STAGE(N)-1400.16
176 GO TO 200
200 CONTINUE
    TRIK = AREA(N)*100.
    NTRIK = TRIK
    IF ((TRIK-(FLOAT(NTRIK)/100.))-0.005)600,610,620
600 AREA(N) = FLOAT(NTRIK)/100.
    GO TO 201
610 IF (2*(NTRIK/2).EQ.NTRIK)GO TO 600
620 AREA(N) = FLOAT(NTRIK)/100.+0.01
201 ATA(N) = AREA(N)*AT(N)
205 WRITE(6,5)STAGE(N),AT(N),AREA(N)
210 IF (N.LT.K)GO TO 10
212 N = 1
215 ENERGY = 0.0
220 ENERGY = ENERGY + ((ATA(N)+ATA(N+1))*((STAGE(N)-STAGE(N+1))/2.0))
225 IF (N+1.EQ.K+1)GO TO 300
230 IF (N+1.EQ.K)GO TO 250
```

TABLE C-I (Continued)

```
  235 N = N+1
  240 GO TO 220
  250 N = N+1
  260 ATA(N+1) = 0.0
  270 STAGE(N+1) = 1110.00
  280 GO TO 220
  300 ENERGY = ENERGY*0.123349E10
      SUMAR = 0
      SUMAT = 0
  301 DO 304 J=1,K
      SUMAR = SUMAR + AREA(J)
      SUMAT = SUMAT + ATA(J)
  304 CONTINUE
      WAVTP = SUMAT/SUMAR
      WRITE(6,410)WAVTP
  305 WRITE(6,6)ENERGY
      WRITE(6,935)
      GO TO 8
  310 STOP
      END
$ENTRY
```

VITA

William Earl Fry

Candidate for the Degree of

Master of Science

Thesis: DETERMINATION OF EVAPORATION AT LAKE HEFNER BY ENERGY AND WATER BUDGET METHODS - 1965.

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Canadian, Texas, February 10, 1939, the son of Charles E. and Mary M. Fry.

Education: Attended grade school in Rogers, Arkansas; Canadian, Higgins, and Amarillo, Texas; graduated from Amarillo High School in 1957; received the Associate in Science degree from Amarillo Junior College, with a major in Pre-Engineering, in May, 1959; received the Bachelor of Science degree from Oklahoma State University, with a major in Agricultural Engineering, in May, 1965; completed requirements for the Master of Science degree in May, 1967.

Professional experience: Student trainee engineer, U.S.D.A., A.R.S., summers of 1958 and 1959; Technical Assistant, State of Texas, Texas Agricultural Experiment Station, October, 1959 to May, 1960; Engineering Technician, U.S.D.A., A.R.S., May, 1960 to February, 1965; Graduate Research Assistant, Oklahoma State University, February, 1965 to June, 1965; Project Engineer, Oklahoma State University, June 1965 to September, 1965; Graduate Research Assistant, Oklahoma State University, September, 1965 to July, 1966; Associate member of the American Society of Agricultural Engineers; Registered Engineer-in-Training, State of Oklahoma; Junior Member of Oklahoma and National Societies of Professional Engineers.