HEAT AND MASS TRANSFER EQUATIONS FOR PREDICTING EVAPORATION REDUCTION BY MONOLAYERS

By

HARRY LEO MANGES

Bachelor of Science
Kansas State University
Manhattan, Kansas
1949

Master of Science
Kansas State University
Manhattan, Kansas
1959

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
August, 1969

STATE UNIVERSITY
LIBRARY

NOV 5 1969

HEAT AND MASS TRANSFER EQUATIONS FOR PREDICTING EVAPORATION REDUCTION BY MONOLAYERS

Thesis Approved:

F. R. Crow
Thesis Adviser

E. W. Schroeder

James E. Garton

J. A. Wiebelt

John F. Stone

D. D. Durham
Dean of the Graduate College

730022

PREFACE

Financial support for the experimental phase of this study was provided by the U. S. Bureau of Reclamation, Contract No. 14-06-D-5629. The research contract was administered jointly by the Oklahoma State University Office of Engineering Research and the Oklahoma Agricultural Experiment Station.

Appreciation is extended to the Ford Foundation for providing a forgivable loan and the Agricultural Engineering Department of Oklahoma State University for providing a research assistantship. This endeavor could not have been completed without their financial assistance.

I am especially grateful to Associate Professor Franklin R. Crow of the Agricultural Engineering Department, my thesis adviser, for his encouragement, guidance, and helpful criticism during the research and writing of the thesis. I am also grateful to Professor James E. Garton of the Agricultural Engineering Department, chairman of the advisory committee, for his helpful comments.

I wish to thank Professor E. W. Schroeder, Head of the Agricultural Engineering Department and member of the advisory committee, for his help in entering the graduate program and his support of the research. Thanks are extended to Professors John F. Stone of the Agronomy Department and John A. Wiebelt of the Mechanical Engineering Department for their assistance while serving on the advisory committee.

Appreciation is extended to the personnel of the research laboratory and the draftsmen of the Agricultural Engineering Department for their contribution to the research and thesis. Appreciation is also extended to Mrs. Sandra Carroll, Mrs. Linda Manning and Mrs. Linda Parrish for typing the final draft of this thesis.

Grateful thanks are given to Elaine, my wife, and to my children for the personal sacrifices they made during this endeavor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The Problem

Surface reservoirs store water for cities, towns, irrigation, industry and generation of hydroelectric power. Reservoirs on streams increase the area of water exposed to evaporation. Large volumes of water are evaporated and made unavailable to beneficial uses. Evaporation not only removes large volumes of water from storage but lowers the quality of that remaining. Pure water evaporates leaving behind salts and other material thereby increasing the concentration of dissolved matter in the remaining stored water.

It was first observed in laboratory experiments that some organic compounds form a film one molecule thick on water. These films or monolayers significantly reduced evaporation. Field tests indicated that fatty alcohols, principally hexadecanol and octadecanol, will form a compressed monolayer which reduces evaporation if a complete film cover can be maintained. However, under natural conditions the monolayer was readily blown from the water surface.

Research activity is increasing to find ways of eliminating unnecessary evaporation from storage reservoirs. The Federal Council for Science and Technology Committee on Water Resources Research (1966) recommends a three-fold increase in research on water yield improvement as soon as possible. Evaporation suppression is included in this category. Specific items needing expanded effort are systems to maintain a complete film cover on reservoirs and chemicals with better staying power.

Accurate procedures are necessary to evaluate the performance of monolayer forming chemicals and chemical distribution systems. Evaporation with the monolayer present must be determined along with an estimate of what the evaporation would have been without a film cover. Ideally, this could be accomplished by using two identical reservoirs, treating one with a monolayer and the other serving as a check. Duplicate large reservoirs are not available and not practical to construct. Thus it becomes necessary to determine evaporation from parameters that can be measured when the reservoir has a film cover.

The standard procedure for evaluating the performance of a monolayer is the combined method, a combination of energy budget and mass transfer techniques. One season is spent collecting the necessary data to evaluate the coefficients for the heat and mass transfer equations without a film on the reservoir. In subsequent seasons a monolayer is applied and evaporation determined by an energy budget. Evaporation that would have occurred is estimated by the combined method using coefficients found during the first season. Although the values of the coefficients show a seasonal trend, a constant average value is used in the combined method.

Objectives

The objectives of this study were:

1. To develop heat and mass transfer equations with constant coefficients to determine evaporation

from treated and untreated reservoirs.

2. To develop a procedure for estimating evaporation reduction by a monolayer based on heat and mass transfer equations.
3. To compare the developed equations and procedure with presently used equations and procedures.

Scope of Investigation

This study was conducted on paired ponds of approximately one-fourth acre surface area. The ponds were lined with sheets of polyvinyl chloride to prevent seepage. Evaporation was measured by an accurate water budget which provided a base for evaluating evaporation equations. Instruments were installed to measure all the variables in the heat and mass transfer equations and the water and energy budgets.

One pond served as a check throughout the study. A slurry mixing and automatic distribution system was installed to deliver monolayer forming chemical to the other pond. Sufficient chemical was applied to maintain a complete film cover on the treated pond.

The research reported in this dissertation was conducted from August 13 to October 23, 1965. The monolayer forming material was long chain alcohols in powdered form of the following composition: 2% C_{14}, 29% C_{16}, 61% C_{18}, 5% C_{20}, and 3% non-alcohol.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Stream flow provides most of the water used in the United States. Langbein and Wells (1955) state that rivers and creeks supply 75 percent of the water used by cities and towns and farmers for irrigation, 90 percent of the fresh water used by industry, and nearly all the water used to generate hydroelectric power.

Storage reservoirs have been constructed to provide water during periods of low stream flow. Operating reservoirs have been enlarged and additional reservoirs constructed to satisfy increasing water demands. The most economical reservoir sites have been used. In some areas sufficient reservoir capacity is available to store normal stream yield. Conservation of stored water is now receiving its deserved emphasis.

Evaporation consumes a large volume of water from storage reservoirs. Crow and Daniel (1958) found that evaporation was 12 times as great as farmstead use from a farm pond in Oklahoma. They also reported that evaporation from Lake Carl Blackwell, a 3500 acre lake, was over four times greater than the domestic use by a population of 20,000 persons. Harbeck and Koberg (1959) state that annual gross evaporation from Lake Mead ranged from 699,000 to 875,000 acre feet during the water years 1953-1956. Evaporation losses are not confined to arid and semi-arid regions. According to Silveston (1965) mean annual evaporation from lakes and ponds in the United States varies from 20 inches in the northeast to over 80 inches in the southwest. He estimates a mean annual loss to evaporation of 40 inches for the continental United States.

Monolayers for Reducing Evaporation

The ability of some organic compounds to form a film on a liquid surface was first observed in 1899. It was not until 1924 that attempts to retard evaporation with monolayers were reported. These organic chemicals form a film one molecule thick which is one-ten millionth of an inch. The films do not interfere with oxygen and carbon dioxide transfer between water and air. Numerous tests by the Bureau of Reclamation and other investigators have been made to determine the effect of monolayers on human and aquatic life. No undesirable effects on public health, water quality, fish or wildlife have been found.

Hedestrand (1924) and Adam (1925) in laboratory studies found the same rate of evaporation for a clean water surface as for a water surface covered with a monolayer. The limiting factor in these studies was the capacity of the air currents to remove the water vapor. The rate of evaporation from a water surface with a fatty acid monolayer was found to be much slower than from a clean water surface (Rideal, 1925). Evaporation was reduced 52.5 percent by a monolayer of Oleic acid when the water temperature was 25 degrees Centigrade. An increase in water temperature reduces the evaporation retarding ability of a monolayer.

Mansfield (1953) was unsuccessful in his first attempt to suppress evaporation with a monolayer of hexadecanol under natural conditions.

He realized the potential of the fatty alcohols in reducing evaporation and continued his investigations. Mansfield (1955) stated that a film of hexadecanol should reduce natural evaporation by 70 percent. However, any reduction in evaporation raises the water temperature. As a result of increased water temperature, Mansfield (1955) predicted a mean evaporation reduction of 45 percent for summer conditions in inland southern Australia.

Researchers have met with varying degrees of success in suppressing evaporation with monolayers. Vines (1960) reduced evaporation approximately 50 percent in one month on a 250 to 300 acre lake in Australia. A fine powder, approximately of equal portions of hexadecanol and octadecanol, was dusted onto the water surface from a boat. During the entire month weather was ideal with winds below 5 miles per hour and temperatures below 80 degrees Fahrenheit. In east-central Illinois, Roberts (1962) reported evaporation reductions of 22 and 43 percent on a 2.5 acre pond. The chemical was applied from three pots as a slurry of hexadecanol and pond water. The smaller evaporation reduction was obtained in a season in which natural evaporation was 30 percent less than when the larger reduction was measured.

A large scale field study was conducted on Lake Hefner, a 2500 acre water supply reservoir for Oklahoma City, Oklahoma, in 1958. The monolayer forming slurry was distributed from a barge and boats. Florey and other (1959) reported a 9 percent reduction in evaporation from an average coverage of 10 percent during an 86-day period. For individual periods of about 10 days the evaporation savings were 7 to 14 percent (Timblin and others, 1962). Results from the Lake Hefner study indicate a poor monolayer cover when winds were over 15 miles per hour. When winds were over 19 miles per hour, it was usually impossible to maintain any cover. An investigation, similar to the Lake Hefner study, was conducted at Pactola reservoir in South Dakota. Runkles and others (1964) reported an average evaporation reduction of 14 percent. The average wind speed during the treatment periods was 5.8 miles per hour.

Monolayers suppress evaporation in calm weather with savings up to 50 percent. However the savings are less under windy conditions. The film is broken up by wind and blown across the water surface along with the excess chemical needed for film formation. When the wind dies, the film will reform and complete cover is achieved.

Water Budget

A water budget measures directly gain or loss of storage in a reservoir. The water budget is based on the Law of Conservation of Mass. Therefore, the change in mass storage is equal to the mass entering minus the mass leaving. Assuming the density of water is constant, the equation for evaporation by the water budget is

$$E = S_1 + I_s + I_u + P - S_2 - O_s - O_u \tag{1}$$

where

E = volume of evaporated water
S_1 = volume of initial storage
I_s = volume of surface inflow
I_u = volume of sub-surface inflow
P = volume of precipitation
S_2 = volume of final storage

O_s = volume of surface outflow

O_u = volume of seepage.

Change in storage, surface inflow and outflow, and precipitation can usually be measured. However, sub-surface inflow and seepage must be estimated by indirect methods such as observation of groundwater levels and permeability measurements. Langbein and others (1951) reported that seepage and evaporation can be estimated by simultaneous solutions of water budget and mass transfer equations.

The water budget is direct and theoretically accurate for determining evaporation from a reservoir. However, evaporation is the residual and therefore subject to considerable error if it is small compared to the other terms in the water budget equation. Unfortunately an accurate water budget is possible for only a few reservoirs. Other techniques are necessary to determine evaporation from most water storage reservoirs.

Mass Transfer

Dalton was the first to point out that evaporation is proportional to the difference between vapor pressure of the air at the water surface and that of the overlying air. Although he apparently never expressed the relationship in mathematical form, later writers have expressed his statement by the equation

$$E = C(e_s - e_d) \tag{2}$$

where

E = evaporation

C = coefficient whose value depends on wind velocity and other variables

e_s = vapor pressure of saturated vapor at the temperature of the water surface

e_d = vapor pressure of saturated air at the temperature of the dewpoint.

Many investigators have attempted to determine the correct mathematical relationship of the law discovered by Dalton. The difficulty of accurately measuring evaporation during short time intervals when meteorological conditions remain constant has overshadowed the effects of the variables. As a result, meteorological variables have been averaged over a period of time by various investigators.

Fitzgerald (1886) made a series of evaporation studies both under controlled laboratory conditions and natural conditions. He proposed the equation

$$E = (0.40 + 0.20\ W)\ (e_s - e_d) \qquad (3)$$

where W is the mean velocity of ground wind in miles per hour. Fitzgerald made no correction for altitude but concluded that evaporation should increase with the altitude if other conditions remain the same.

In a series of evaporation experiments conducted for the United States Weather Bureau, Bigelow (1907-1910) developed the equation

$$E = C_2 \frac{e_s}{e_d} \frac{de}{ds} (1.0 + 0.07\ W) \qquad (4)$$

where

E = evaporation in centimeters per day

e_s and e_d = vapor pressures in millibars

W = wind velocity in kilometers per hour

$\frac{de}{ds}$ = the rate of change of the vapor pressure in the saturated condition, with temperature

C_2 = coefficient whose value depends on the size of the reservoir.

The values of C_2 were 0.042, 0.037 and 0.032 for 2-, 4-, and 6-foot diameter evaporation pans, respectively. The values of the coefficients in the Bigelow equation were found to be the same for both arid and humid regions of the United States.

From theoretical considerations, Horton (1917) presented the equation

$$E = C(\Psi\ e_s - e_d) \tag{5}$$

where

C = coefficient of proportionality that includes reservoir size

Ψ = coefficient that accounts for wind velocity

According to this equation, condensation occurs when $e_d > \Psi e_s$. For constant vapor pressures, wind tends to decrease condensation and increase evaporation. Most evaporation equations are of the form, $E = C(e_s - e_d)$ and the effect of wind is to increase both condensation and evaporation.

Himus (1929) developed the equation

$$E = 0.02\ (e_s - e_d)^{1.2} + 0.0446\ U^{0.77}\ (e_s - e_d)^{0.83} \tag{6}$$

where

E = evaporation in kilograms per square meter per hour

U = wind velocity in meters per second.

The first group of terms account for evaporation into still air and is analogous to heat transfer in free convection. Vapor pressure difference has an exponent of 1.2 which is comparable to the temperature difference for heat transfer which has an exponent of 1.23. The second group of terms account for evaporation into moving air and is analogous to heat transfer in forced convection. Wind velocity has an exponent of 0.77 compared to 0.80 for heat transfer in forced convection with turbulent flow.

Rohwer (1931) conducted extensive evaporation experiments both in the laboratory and under natural conditions. For evaporation from evaporation pans he developed the equation

$$E = (1.465 - 0.0186\ B)(0.44 + 0.118\ W)(e_s - e_d) \qquad (7)$$

where

B = mean barometer pressure in inches of mercury

W = wind velocity in miles per hour at ground level

For large lakes and reservoirs Rohwer proposed the equation

$$E = 0.771\ (1.465 - 0.0186\ B)(0.44 + 0.118\ W)(e_s - e_d). \qquad (8)$$

Braslavskii and Vikulina (1963) stated that probably the best existing empirical evaporation equation is that of Zaikov,

$$E = 0.15\ n\ (1.0 + 0.72\ W)(e_o - e_a) \qquad (9)$$

where

E = evaporation in millimeters per month

n = number of days in the month

W = wind velocity at a height of 2 meters in meters per second

e_o = saturated vapor pressure of air at the water surface temperature in millibars

e_a = vapor pressure of the air at a height of 2 meters in millibars.

The numerical values of the coefficients were determined from measurements at evaporation stations throughout Russia and other published evaporation data.

Equations 2 through 9 are empirical equations derived by graphical and statistical techniques to equate evaporation to measured meteorological data. Other investigators have attempted to evaluate the coefficient to the vapor pressure deficit on a more theoretical basis. Eleven such evaporation equations were selected for comparison with the water budget in the 1950-1951 Lake Hefner studies. Marciano and Harbeck (1954) reported that Sverdrup's and Sutton's equations overestimated evaporation from Lake Hefner by 12 and 7 percent, respectively.

Sverdrup (1937) developed an evaporation equation from observations on the sea. He used a two-layer model with the assumptions that:

1. A laminar boundary layer exists next to the water surface within which transport of water vapor is by diffusion.
2. Above the laminar layer is a turbulent layer within which transport of water vapor is by eddy conductivity.

3. The water surface can be considered rough and is characterized by the roughness parameter, z = 0.6 centimeters.

The equation can be expressed as

$$F = \frac{0.623\ \rho\ u^* (e_o - e_a)}{P[\frac{1.0}{k_o} \quad \ln \quad \frac{z + z_o}{d + z_o} + \frac{u^*d}{D}]} \tag{10}$$

where

F = evaporation in grams per square centimeter per second

ρ = density of the air in grams per cubic centimeter

k_o = a numerical constant equal to 0.38

u^* = friction velocity in centimeters per second

e_o = vapor pressure of saturated air at the water surface temperature in millibars

e_a = vapor pressure of the air at height z above the water surface in millibars

P = barometer pressure in millibars

z = height of temperature and wind velocity measurement, usually 6 meters

z_o = roughness parameter with numerical value of 0.6 centimeters

d = thickness of the laminar layer in centimeters

D = coefficient of diffusion in square centimeters per second.

The numerical value of d can be calculated from the equation

$$d = \frac{27.5\ \nu}{u^*} \tag{11}$$

where ν is the kinematic viscosity of the air. Sverdrup's equation estimates "point" evaporation with total evaporation from a reservoir equal to F times the area. The height, z, where wind velocity and temperatures are measured must be within the vapor boundary layer.

Sutton (1949) developed an equation for evaporation from a smooth surface. Marciano and Harbeck (1954) stated that Sutton's equation modified for a circular reservoir with a rough surface is

$$E = \frac{0.623}{P} \rho G' u^{\frac{2-n}{2+n}} r^{\frac{4+n}{2+n}} (e_o - e_i) \tag{12}$$

where

E = volume of evaporated water in unit time

P = barometer pressure

G' = coefficient whose numerical value depends on n, wind velocity and height, z, of wind velocity measurement

n = positive constant whose numerical value depends on the wind velocity profile

u = average wind velocity

r = radius of the reservoir

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

e_i = vapor pressure of unmodified air.

This is Sutton's 1949 equation that was tested in the 1950-1951 Lake Hefner studies. Sutton assumed that the wind velocity profile can be approximated by the power law,

$$\frac{u}{u_o} = (\frac{z}{z_o})^{\frac{1}{p}} \qquad (13)$$

where

u = wind velocity at height z

u_o = wind velocity at a known height z_o

p = exponent whose numerical value is approximately 7.

When p = 7, the numerical value of n is 0.25. Thus the wind velocity, u, has an exponent of 0.78 and the radius, r, has an exponent of 1.89. For Sutton's equation the wind velocity and vapor pressure of the air must be measured above the vapor boundary layer.

During the 1950-1951 Lake Hefner studies, an empirical equation was developed from water budget evaporation, wind speed and vapor pressure difference (Marciano and Harbeck, 1954). This equation is

$$E = 6.25 \times 10^{-4} U_8 (e_o - e_8) \qquad (14)$$

where

E = evaporation in centimeters per 3 hours

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

e_o = vapor pressure of saturated air at the water surface temperature in millibars

e_8 = vapor pressure of the air 8 meters above the water surface in millibars.

Harbeck (1952) reported an evaporation equation for Lake Hefner using wind and humidity data from Will Rogers Airport located 13 miles to the south. Average daily water surface temperatures were recorded at the center of Lake Hefner. The equation is

$$E = 6.47 \times 10^{-4} U(e_o - e_a). \tag{15}$$

A striking result from the Lake Hefner study is that daily evaporation can be accurately predicted by neglecting atmospheric stability (Marciano and Harbeck, 1954). Also, evaporation can be accurately estimated by using vapor pressure of unmodified air in place of vapor pressure above the water surface if the value of the coefficient is adjusted.

Harbeck and others (1958) reported the results of evaporation studies at Lake Mead. Neither Sverdrup's 1937 equation nor Sutton's 1949 equation gave an accurate estimate of evaporation when compared with the energy budget. On an annual basis, evaporation calculated with the Lake Hefner empirical equation was in excellent agreement with the energy budget. However, deviations of considerable magnitude were observed for individual periods of about a month. These deviations had a definite seasonal trend.

The Lake Hefner mass transfer equation subsequently was used at various reservoirs including Lake Hefner, Sahuaro Lake, Lake Cachuma, Pactola Reservoir and Elephant Butte Reservoir. The form of the equation used is

$$E = Nu\ (e_o - e_a) \tag{16}$$

where N is the mass transfer coefficient. The numerical value of N determined at these locations appears to have a seasonal variation similar to that found at Lake Mead.

Millar (1937) proposed that evaporation is proportional to $u^{0.75}\ (e_o - e_a)$ for average atmospheric stability. Langbein and others

(1951) confirmed a value of about 0.75 for the exponent of the wind speed.

According to Sutton (1949) evaporation per unit area is proportional to $f^{-0.11}$ where f is the length of the water surface. He reasoned that an air stream grows richer in water vapor as it progresses across a water surface. Measurements made under natural conditions indicate that evaporation rates are approximately constant for stretches of water exceeding 12 feet (Sleight, 1917; Rohwer, 1931). Mansfield (1958) concludes that the disappearance of the exponent for the length term arises from compensating changes in the nature of flow over large areas and from adjustment of heat balances.

Energy Budget

The theory of the energy budget is based on the Law of Conservation of Energy. Energy which comes into a reservoir must equal the gain in stored energy plus the energy that leaves the reservoir. Incoming energy comes from the sun, atmosphere, precipitation and inflow, while outgoing energy goes into radiation, heat conduction, evaporation and outflow.

Schmidt (1915) attempted to utilize the energy budget to estimate evaporation from the oceans. He neglected the change in stored energy by computing evaporation over a period of one year. Also, Schmidt treated the ratio of sensible heat carried away from the water surface by convection to latent heat of evaporated water as a positive constant. This inferred that sensible heat always moves out of the water or, stated another way, the ocean is always warmer than the overlying air.

Evaporation from Lake Vassijaure in Sweden was estimated by Angstrom (1920) using an energy budget balance.

After experimenting with a thermally insulated jar, Cummings (1925) stated that,

> radiant energy per cm squared integrated over any time interval was equal to the heat represented by the change in temperature of the water plus the heat represented by the evaporation per cm squared during the same time interval plus a relatively small correction to be determined empirically. This correction appears to depend on atmospheric conditions.

Bowen (1926) expressed Cummings' statement by the equation

$$I = S + LE + K \tag{17}$$

where

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

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

LE = heat represented by evaporation, E, with L being the latent heat of vaporization

K = correction for other losses.

The other losses represented by K are due to conduction and convection from the water surface.

Bowen (1926) concluded that the process of evaporation and diffusion of water vapor from any water surface into the overlying body of air is exactly similar to that of conduction of specific heat energy from the water surface into the same body of air. Because of this similarity the ratio, which bears Bowen's name, of the heat loss by conduction to that by evaporation can be expressed by the equation

$$R = c\left(\frac{T_o - T_a}{e_o - e_a}\right) \frac{P}{1000} \tag{18}$$

where

R = Bowen ratio

c = coefficient of proportionality

T_o = temperature of the water surface in degrees Centigrade

T_a = temperature of the air in degrees Centigrade

e_o = vapor pressure of saturated air at the water surface temperature in millibars

e_a = vapor pressure of the air in millibars

P = barometer pressure in millibars.

The limiting values of c were found to be 0.58 and 0.66 depending upon the state of the atmosphere. Bowen concluded that under normal atmospheric conditions, c is approximately 0.61. Using the Bowen ratio, the energy loss by conduction and convection, K, can be expressed as

$$K = R(LE). \tag{19}$$

Substituting for K in equation 17 gives

$$I = S + LE\ (1 + R) \tag{20}$$

which Bowen (1926) states is an exact equation for any body of water that is thermally insulated on the sides and bottom.

An experiment with a well insulated pan and a tank was conducted by Cummings and Richardson (1927). Evaporation was calculated by the equation

$$E = \frac{H - S - C}{L\ (1 + R)} \tag{21}$$

where

E = evaporation

H = difference between incoming and outgoing radiation

S = heat stored in a column of water having unit cross-section

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

L = heat of vaporization

R = Bowen's ratio.

The value of H was determined for the insulated pan and used to estimate evaporation from the tank. It was concluded that if a technique could be developed to determine back-radiation from the water surface, the insulated pan would not be needed.

Richardson (1931) studied the effects of insulation on evaporation. Incoming radiation was calculated from pyreheliometer readings and back-radiation was calculated from the Stefan-Boltzmann relation. Sensible heat and conduction for a short period or over a yearly cycle were found to be negligible from data collected in California.

Using a thermally insulated pan to measure radiation terms, Cummings (1940)computed evaporation by Equation 21 from Bear Lake in Utah and Idaho. A control was lacking and Cummings could only compare computed evaporation with measured evaporation from Weather Bureau Class A pans.

Sverdrup (1940) applied the energy budget to the Bay of Biscay which was without distinct currents so that advected energy could be considered negligible. He also investigated the waters of the Kuroshio of the region south of Japan where distinct currents existed and advected energy was considered constant throughout the year.

After analyzing the energy budget in detail, Holzman (1941) concluded that:

> The heat-balance method for determining evaporation from water-bodies is known to be theoretically precise. However, the difficulties to be encountered in accurately measuring most of the essential parameters in the heat-balance equation appear to invalidate the practical usefulness of the technique.

Holaman was justified in his statement considering the stage of development of radiation measuring instruments.

A rigorous evaporation study was conducted at Lake Hefner near Oklahoma City, Oklahoma, in 1950 and 1951. The investigation used the most recent developments in instrumentation and proved, for the first time on a large scale, the soundness of the energy budget in determining evaporation (Anderson, 1954). The energy budget equation developed, expressed as energy per unit area per unit time, was

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_w - Q_h - Q_e = Q_o \qquad (22)$$

where

Q_s = incoming solar or short-wave radiation

Q_r = reflected short-wave radiation

Q_a = incoming atmospheric or long-wave radiation

Q_{bs} = back radiation emitted by the water surface according to the Stefan-Boltzman Law for a gray body

Q_v = net advected energy into the body of water

Q_w = energy advected with the evaporated water

Q_{ar} = reflected long-wave radiation

Q_h = energy transferred between the water surface and overlying air as sensible heat

Q_e = energy required to change the evaporated water to the vapor state without a change in temperature

Q_o = net change in stored energy.

Conduction of energy through the bottom, heating due to chemical and biological processes and the transformation of kinetic energy into thermal energy were neglected because of their small magnitude.

Equation 22 can be rewritten as

$$Q_e + Q_h + Q_w = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_o \qquad (23)$$

The energy used in evaporation, Q_e, is

$$Q_e = E\rho L \qquad (24)$$

where

E = volume of evaporated water in cubic centimeters

ρ = mass density of evaporated water in grams per cubic centimeters

L = latent heat of vaporization at the water surface temperature in calories per gram.

The sensible heat, Q_h, can be written as a function of latent heat using Bowen's ratio, R, giving

$$Q_h = RQ_e = R(E\rho L). \qquad (25)$$

The energy advected with the evaporated water, Q_w, can be expressed as

$$Q_w = \rho \; E \; c_p \; (T_o - T_b) \qquad (26)$$

where

ρ = mass density of water in grams per cubic centimeters

c_p = specific heat of water at constant pressure

T_o = evaporated water temperature, water surface temperature, in degrees Centigrade

T_b = arbitrary base temperature usually taken as 0 degrees Centigrade.

After substituting for Q_e, Q_h and Q_w in Equation 23 and rearranging terms, the volume of evaporated water, E, becomes

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_o}{\rho[L(1 + R) + c_p(T_o - T_b)]} \qquad (27)$$

Anderson (1954) made a comparison of evaporation from Lake Hefner by the energy budget and the water budget for only those days with the most accurate water budget. He concluded that the standard error of estimate by the energy budget was 0.25 centimeters for daily periods, 0.14 centimeters for 4-day periods and 0.05 centimeters for 10-day periods.

Further evaporation studies were conducted at Lake Hefner during 1965. Fry (1967) compared evaporation by the energy budget with evaporation by the water budget. He reported the relation

$$E_{EB} = -0.0315 + 1.27\ E_{WB} \qquad (28)$$

where

E_{EB} = evaporation by the energy budget

E_{WB} = evaporation by the water budget.

For periods of approximately one week, energy budget evaporation exceeded water budget evaporation in 14 of the 18 periods.

Hughes (1967) determined evaporation from the Salton Sea in California by the water budget, energy budget and mass transfer methods. Determinations by the water budget and energy budget for one- and two-year periods differed by less than 5 percent. Comparisons of evaporation determined by the three methods for periods of 10 to 29 days indicated a marked seasonal bias in energy budget evaporation. Computed energy budget values were as much as 60 percent lower than water budget evaporation during the winter and 25 percent higher during the summer. Hughes concluded the principal cause of the seasonal bias was inadequate measurement of total incoming radiation by the flat plate radiometer.

Evaluating Evaporation Reduction

In order to evaluate the effectiveness of a monolayer in reducing evaporation, it is necessary to know both the evaporation which occurs with the film present and the evaporation which would have occurred if no film had been present.

Vines (1962) used a water budget to determine evaporation from a treated reservoir and a pan-to-lake relationship to estimate what the evaporation would have been without a monolayer. He found that monthly evaporation from an untreated reservoir, E_v, can be estimated by the equation

$$E_v = s + n\,E_s \tag{29}$$

where

s = seepage loss

n = a constant for the reservoir

E_s = monthly evaporation from a standard evaporimeter pan.

Kohler (1954) found that the monthly coefficients for various types of evaporation pans vary seasonally for Lake Hefner. Application of this method for estimating evaporation reduction is limited by the need of an accurate water budget and by the possible seasonal variation in pan coefficients.

By solving equations based upon energy budget and heat and mass transfer theory, Harbeck and Koberg (1959) developed a method of evaluating evaporation reduction due to a monolayer. The method involves the computation of two unknowns; the evaporation from the treated reservoir and the water surface temperature that would have been observed had no monolayer been applied.

Evaporation from a reservoir was determined by the energy budget, Equation 22 which can be rewritten as

$$(Q_s - Q_r + Q_a - Q_{ar} + Q_v) - (O_{bs} + Q_e + Q_h + Q_w) = Q_o \qquad (30)$$

It was assumed that the application of a monolayer will not affect the first group of terms in Equation 30.

The water surface temperature increases when a monolayer is applied and, therefore, stored energy increases. As the water temperature increases, the return of energy to the atmosphere by back radiation and conduction increases. Harbeck and Koberg assumed that the water temperature increases until the energy which would have gone into evaporation is dissipated by the increase in back radiation and conduction. When this point is reached, change in stored energy due to the monolayer becomes negligible. Also, energy advected with the evaporated water is small compared with the remaining terms and can be ignored.

The presence of a monolayer has a marked effect on the three remaining terms in the energy budget equation. It follows that the net sum of these effects must be zero or

$$(Q'_{bs} - Q_{bs}) + (Q'_e - Q_e) + (Q'_h - Q_h) = 0 \qquad (31)$$

where the terms with primes refer to the reservoir with a film and the terms without primes refer to the same reservoir without a film. If evaporation is reduced, then $Q'_e - Q_e < 0$ and $(Q'_{bs} - Q_{bs}) + (Q'_h - Q_h) > 0$.

Back radiation to the atmosphere, Q_{bs}, was calculated for both a treated and an untreated reservoir by the equation

$$Q_{bs} = 0.97 \ \sigma(T_o + 273.16)^4 \qquad (32)$$

where

0.97 = emissivity of water

σ = Stefan-Boltzmann constant for black body radiation

T_o = water surface temperature in degrees Centigrade.

Prior to the application of a monolayer, the energy lost to the atmosphere by conduction can be calculated by Equations 18 and 25. After the monolayer is applied, Bowen's ratio is no longer valid. Energy lost to the atmosphere by conduction, Q_h, was calculated for both the treated and the untreated reservoir by the heat transfer equation

$$Q_h = Ku \ (T_o - T_a) \qquad (33)$$

where

K = an empirical constant

u = wind velocity

T_o = water surface temperature

T_a = overlying air temperature.

The energy going into evaporation for the treated reservoir, Q_e', was calculated by the energy budget, Equations 27 and 24. The energy which would go into evaporation if no film were present, Q_e, was estimated by the mass transfer equation

$$Q_e = Nu\ (e_o - e_a) \tag{34}$$

where

N = an empirical constant

u = wind velocity

e_o = saturated vapor pressure at the water surface temperature

e_a = vapor pressure of the overlying air.

Substituting Equations 32, 33 and 34 into Equation 31 gives

$$\begin{aligned} &0.97\ \left[(T_o' + 273.16)^4 - (T_o + 273.16)^4\right] + \\ &[Q_e' - Nu(e_o - e_a)] + Ku\ (T_o' - T_o) = 0 \end{aligned} \tag{35}$$

where the primed terms refer to the treated reservoir. Equation 35 is a function of T_o only since e_o is a function of T_o, but the mathematical relationship is not simple. A trial-and-error solution was used with an assumed value of T_o and the corresponding value of e_o. The surface temperature, assuming no monolayer was present, was found when the assumed value of T_o balanced Equation 35. The energy that would have gone into evaporation, Q_e, assuming no film had been applied was calculated by Equation 34.

The evaporation, if no film was present, E, was calculated by the equation

$$E = \frac{Q_e}{\rho L} \tag{36}$$

where

ρ = mass density of the evaporated water

L = latent heat of vaporization at the water surface temperature.

The evaporation from the treated reservoir, E', as calculated by Equation 27 can be compared with the evaporation if no film was present, E, as calculated by Equation 36 and the performance of the monolayer evaluated.

To evaluate the performance of a monolayer by the method of Harbeck and Koberg, it is necessary to have a calibration period with no film on the reservoir. During the calibration period, evaporation is determined by the energy budget and the coefficients K and N for the heat and mass transfer equations must be evaluated.

Mansfield (1962) pointed out that the heat and mass transfer coefficients for nontreatment periods are not the same as those for treatment periods. Since the presence of the monolayer reduces the development of waves, Mansfield concluded that the wind movement near the water surface would not be the same for treated and untreated reservoirs. Millar (1937) discussed the effect of waves on the wind movement near the water surface and concluded that,

> Waves, which travel with the wind, cannot be expected to exert as much stress as fixed obstacles. Indeed,

waves at sea often run at speed very little less than that of the wind blowing over their crests, and under these circumstances, one would expect the stress and distribution of velocity to be very nearly the same as for a smooth surface.

CHAPTER III

THEORY

Introduction

The effectiveness of a monolayer in suppressing evaporation is commonly evaluated by a combination of energy budget and heat and mass transfer equations developed by Harbeck and Koberg (1959). During the calibration period, evaporation from the untreated reservoir is determined by an energy budget. The numerical values of the coefficients K and N are evaluated for the heat transfer equation, $Q_h = Ku(T_o-T_a)$, and the mass transfer equation, $Q_e = Nu(e_o-e_a)$. Although the numerical value of N varies with the season, an average value is assumed. When the reservoir is treated, evaporation is determined by an energy budget. The evaporation if no film has been applied is estimated by heat and mass transfer relationships. Therefore, the accuracy of the estimate of evaporation reduction is determined by the accuracy of the energy budget. Evaporation is a residual term in the energy budget and any errors in evaluating the energy terms directly affect the magnitude of computed evaporation.

In this Chapter, a procedure is developed to evaluate the performance of a monolayer in suppressing evaporation. Evaporation from a treated reservoir and an estimate of what the evaporation would have been without the monolayer are determined directly by heat and mass transfer equations. Necessary instrumentation is less than for the procedure based on an energy budget as radiation energy does not enter into the calculations and need not be measured.

Heat and Mass Transfer Similarity

Evaporation is analogous to heat transfer from a solid body to air. A thin layer of stagnant air surrounds the solid through which heat is transferred by conduction. Outside the stagnant air, heat is transferred by convection. Heat transfer has been computed successfully by an overall heat transfer coefficient which combines the coefficients of conduction and convection. The temperatures used with this coefficient are the wall temperature of the solid and the air temperature. The rate of evaporation can be calculated in a similar manner. The potential for evaporation is the difference in vapor pressure between the water-air interface and the air. Heat transfer coefficients are correlated by means of dimensionless groups. Similar groups can be used to correlate evaporation coefficients.

Air Flow in the Boundary Layer

Equations of continuity, momentum and energy have been developed for fluid flow. These fundamental equations cannot be solved directly for most practical problems.

Prandtl introduced the concept of two regions of flow. In one region, near the wall between a body and fluid flow, the viscous forces are significant and must be considered. This region was referred to as the boundary layer. In the other region outside the boundary layer, the viscous forces are insignificant and can be ignored. Boundary layer theory has provided an approximate method for solving the momentum and continuity equations and forms the basis for treating evaporation as a mass transfer phenomena.

Boundary layer theory was first developed with momentum as the important property. Scalar fields, such as temperature and vapor pressure, may also be thought of as having boundary layers. The concept of similarity has been used to connect momentum and heat transfer, heat and mass transfer, and momentum and mass transfer. It is generally accepted that turbulent transports of momentum, heat and mass follow the same fundamental laws and that their coefficients of eddy transport are interchangeable (Marciano and Harbeck, 1954).

One of the most studied conditions for fluid flow is the flow of air past a flat plate. Although the earth's surface has a slight curvature, the theory of fluid flow past a flat plate has been assumed to apply for air flowing over the earth's surface.

In nature, the boundary layer over a reservoir is formed as shown in Figure 1. After the air has been flowing some distance over a reasonably uniform surface, the thickness of the boundary layer will be essentially constant with respect to the downstream distance and a velocity profile will be developed. When a water surface is suddenly encountered, a new boundary layer will develop within the fully developed boundary layer. The rate of growth of the new boundary layer will depend on distance from the leading edge of the water surface as well as the properties of the air and the roughness of the water surface.

Millar (1937) concluded that the velocity distribution over a water surface is nearly the same as for a smooth surface. Therefore, it

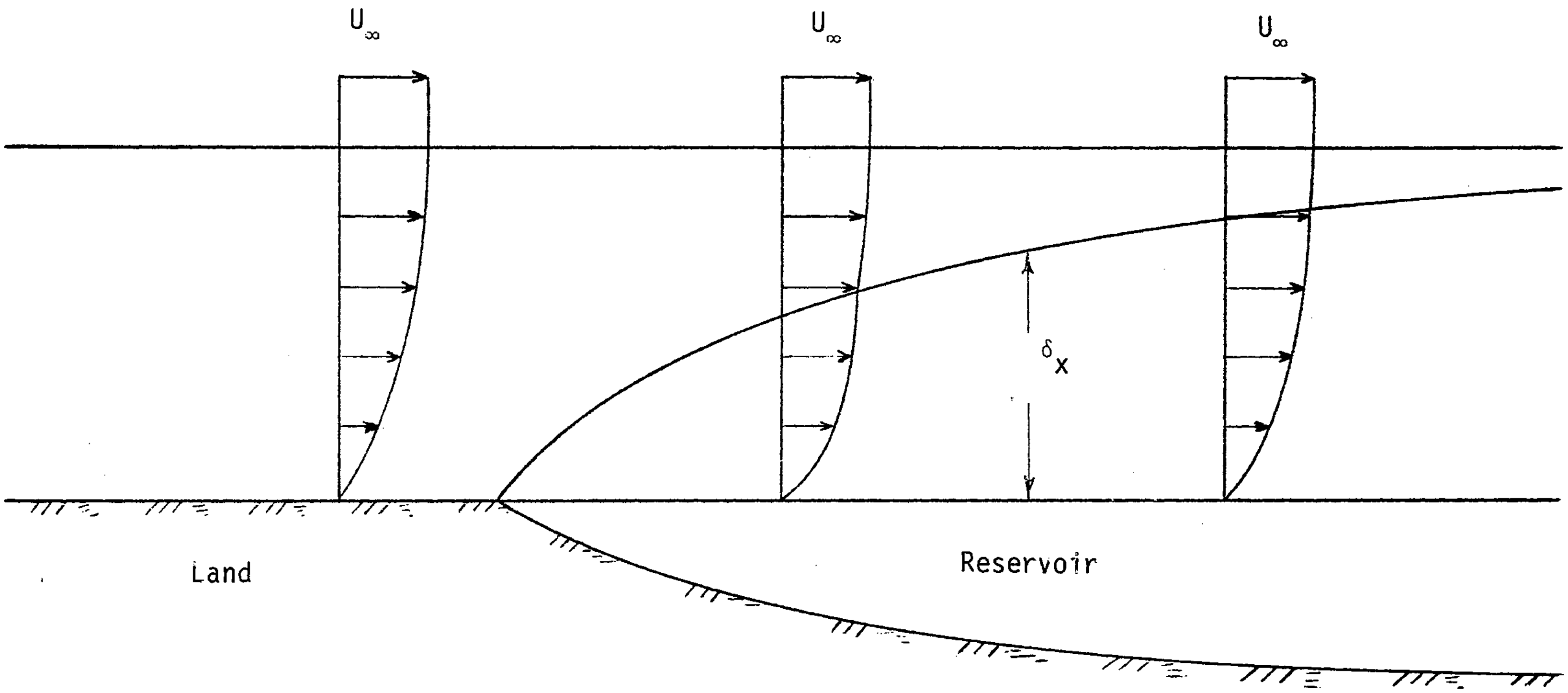


Figure 1. Growth of the Boundary Layer Over a Reservoir.

was postulated that flow in the boundary layer over a reservoir is always turbulent.

The temperature difference between a reservoir surface and the overlying air is relatively small. In such cases the buoyancy forces can be neglected and forced convection exists.

It is generally accepted that the velocity profile above a flat plate follows the logarithmic distribution law. At some distance above the surface, the velocity approaches a constant value, namely the free stream velocity. Marciano and Harbeck (1954) concluded that over most lakes the wind profile between 2 and 8 meters can be approximated by the logarithmic distribution law. The logarithmic distribution law is difficult to handle mathematically so other methods are useful to solve practical fluid flow problems.

A power velocity distribution law is relatively easy to manipulate mathematically. This law is usually written as

$$u = u_i \left(\frac{z}{z_i}\right)^{1/p} \tag{37}$$

where

u = mean wind speed at height z

u_i = mean wind speed at height z_1

z = height at which wind velocity u is desired

z_i = reference height

$1/p$ = a fraction greater than 0 and less than 1.

The validity of a power velocity distribution law is open to question. Schlichting (1960) reported that the value of p increases slightly with increasing Reynolds number for flow through smooth pipes.

Sutton (1932) used observations made by Heywood (1931) for the 100 meters above the earth's surface to determine the value of 1/p. The exponent 1/p varied from 0.07 to 0.17 with the smaller values at noon and the larger values at night. Geiger (1965) concluded that the exponent 1/p is not a constant but varies with wind speed, becoming smaller as wind speed increases. As there is a diurnal variation of wind speed, the value of p changes with time of day. The value of p may also vary with the temperature structure of the air and the roughness of the ground surface.

Heat Transfer

No analytical technique has been found which will solve practical heat transfer problems when flow is turbulent. Empirical and semi-empirical solutions must be used.

Kreith (1966) reported that by dimensional analysis the convective heat transfer for a fluid flowing through a heated tube can be expressed by the relationship

$$\mathrm{Nu} = f(\mathrm{Re}_d, \mathrm{Pr}) \tag{38}$$

where

Nu = Nusselt number

Re_d = Reynolds number based on tube diameter

Pr = Prandtl number.

The Nusselt number is a dimensionless term and is

$$\mathrm{Nu} = \frac{hD}{k}$$

where

h = heat transfer coefficient

D = tube diameter

k = thermal conductivity of the fluid.

The Reynolds number is a dimensionless term and is

$$Re_d = \frac{UD}{\nu} \tag{40}$$

where

U = velocity of the fluid

D = tube diameter

ν = kinematic viscosity of the fluid.

The Prandtl number is a dimensionless term and is

$$Pr = \frac{c_p \mu}{k} \tag{41}$$

where

c_p = specific heat of fluid at constant pressure

μ = viscosity of the fluid

k = thermal conductivity of the fluid.

Schlichting (1960) assumed that heat transfer with fluid flow across a flat plate is similar to heat transfer with fluid flow through a pipe. The distance, x, from the leading edge of the flat plate replaces the tube diameter, D, as the characteristic length. Velocity of the fluid, U_∞, is measured in the free stream above the boundary layer. The heat transfer coefficient, h, becomes the local heat transfer coefficient, h_x. Convective heat transfer from a flat plate can be expressed by the relationship

$$Nu_x = f(Re_x, Pr) \tag{42}$$

where

Nu_x = local Nusselt number

Re_x = Reynolds number based on the distance x.

Reynolds' analogy gives a relationship between the coefficient of heat transfer and the coefficient of skin friction. For turbulent flow along a flat plate, Schlichting (1960) states that

$$Nu_x = \frac{Re_x\ C_{fx}}{2} \quad \text{for } Pr = 1 \tag{43}$$

where

C_{fx} = local skin friction.

The Prandtl number must be equal to 1 for Equation 43 to be valid. In the temperature range encountered in evaporation from a reservoir, Pr for air is approximately 0.7. Colburn (1933) found that for fluids having Prandtl numbers ranging from 0.6 to about 50,

$$Nu_x = \frac{Re_x\ Pr^{1/3}\ C_{fx}}{2}\ . \tag{44}$$

The local coefficient of heat transfer can be calculated by Equation 44 when the local coefficient of skin friction is known.

Schlichting (1960) using the 1/7th-power velocity distribution law developed the equations

$$\delta_x = 0.37\ x\ Re_x^{-0.20} \tag{45}$$

where

δ_x = thickness of the turbulent boundary layer at distance x

and

$$C_{fx} = 0.0576 \, Re_x^{-0.20} . \tag{46}$$

The boundary layer thickness and local skin friction equations are based on empirical relationships where the boundary layer is turbulent from the leading edge and the Reynolds number is less than 10^7. Substituting Equation 46 into Equation 44 gives

$$Nu_x = 0.0288 \, Pr^{1/3} \, Re_x^{0.80} . \tag{47}$$

The local Nusselt number for heat transfer is

$$Nu_x = \frac{h_x X}{k} . \tag{48}$$

Combining Equations 47 and 48 gives the local heat transfer coefficient

$$h_x = \frac{0.0288 \, k \, Pr^{1/3} \, (\frac{U_\infty X}{\nu})^{0.80}}{X} . \tag{49}$$

The free stream velocity, U_∞, is the velocity at the outer edge of the boundary layer. It is difficult to locate the edge of the boundary layer above a reservoir as it varies with distance and wind velocity. Also, a velocity gradient exists as the boundary layer above the reservoir is growing within a boundary layer established for the upwind surface conditions. From the 1/7th-power law, it can be deduced that

$$(\frac{U}{\nu})_\infty = (\frac{u}{\nu})_i \, (\frac{\delta_x}{z_i})^{1/7} . \tag{50}$$

Substituting Equation 45 into Equation 50 and measuring wind velocity, u_i, at a height, z_i, gives

$$\left(\frac{U}{\nu}\right)_{\infty} = \frac{0.868}{z_i^{0.139}} \left(\frac{u}{\nu}\right)_i^{0.972} X^{0.111} . \qquad (51)$$

Assuming that the kinematic viscosity term is carried with the velocity term Equation 49 can be written as

$$h_X = \frac{0.0257}{z_i^{0.111}} \, k \, Pr^{1/3} \, X^{-0.111} \left(\frac{U}{\nu}\right)_{\infty}^{0.80} . \qquad (52)$$

Substituting Equation 51 into Equation 52 gives

$$h_X = \frac{0.0257}{z_i^{0.111}} \, k \, Pr^{1/3} \, X^{-0.111} \left(\frac{u_i}{\nu}\right)^{0.778} . \qquad (53)$$

The kinematic viscosity was written with no subscript as properties of the air are usually evaluated at the average temperature of the surface and the height of velocity measurement.

The mean heat transfer coefficient, h, across a reservoir is

$$\overline{h} = \frac{1}{L} \int_0^L h_X \, dx \qquad (54)$$

where

L = length of reservoir.

Substituting for h_X into Equation 54 gives

$$\overline{h} = \frac{1}{L} \int_0^L \frac{0.0257}{z_i^{0.111}} \, k \, Pr^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} X^{-0.111} \, dx. \qquad (55)$$

Integration of Equation 55 gives

$$\overline{h} = \frac{0.0289}{3i^{0.111}} \, k \, Pr^{1/3} \left(\frac{ui}{\nu}\right)^{0.778} L^{0.889} \qquad (56)$$

The total heat transfer from a reservoir is

$$dq = \bar{h}\,(T_s - T_\infty)\,dA \tag{57}$$

where

T_s = temperature at the water surface

T_∞ = temperature at the edge of the boundary layer.

From Reynolds' analogy, it follows that the boundary layer thickness for the velocity field must be equal to the boundary layer thickness for the temperature field (Schlichting, 1960). Therefore, Equation 57 becomes

$$dq = \bar{h}\,(T_s - T_i)\,dA \tag{58}$$

where

T_i = temperature at the reference height.

The wind is continually shifting direction across a reservoir. However, for a circular reservoir the length across it parallel to the wind direction is constant and

$$dA = 2\,x\,dy \tag{59}$$

written for x-y coordinates with $L = 2x$ and $x = (R^2 - y^2)^{1/2}$ where R is the radius. The total heat transfer becomes

$$\int_0^Q dq = \frac{0.0535}{z_i^{\,0.111}}\,k\,Pr^{1/3}\left(\frac{u_i}{\nu}\right)^{0.778}(T_s - T_i)$$

$$\int_{-y}^{y}(R^2 - y^2)^{0.445}\,dy. \tag{60}$$

Equation 60 can be partially integrated by substitution. Letting $u = y/R$ gives $y = uR$ and $dy = Rdu$. With this substitution, Equation 60 can be written as

$$\int_0^Q dq = \frac{0.0535}{z_i^{0.111}} k \, \mathrm{Pr}^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} R^{1.89} (T_s - T_i) \int_{-1}^{1} (1-u^2)^{0.445} \, du. \qquad (61)$$

The right hand integral of Equation 61 can be solved by ploting u versus $(1 - u^2)^{0.445}$ and finding the area under the curve from $u = -1$ to $u = 1$. By Simpson's rule, this area is 1.604. Complete integration of Equation 60 gives

$$Q = \frac{0.0858}{z_i^{0.111}} k \, \mathrm{Pr}^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} R^{1.89} (T_s - T_i) \qquad (62)$$

Dividing Equation 62 by the area of a circular reservoir gives

$$\overline{Q} = \frac{0.0273}{z_i^{0.111}} k \, \mathrm{Pr}^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} R^{-0.11} (T_s - T_i) \qquad (63)$$

which is the average heat transfer per unit area.

Heat transfer from a circular reservoir can be calculated by Equation 63 with the wind velocity, u_i, measured at height z_i. The restrictions are that the velocity profile can be approximated by a power law with $p = 7$ and that the Reynolds number does not exceed 10^7.

Mass Transfer from Untreated Reservoir

Eckert and Drake (1959) reported that any heat transfer equation for laminar and turbulent flow gives the solution for a corresponding mass transfer problem if the Nusselt number is replaced by the dimensionless mass transfer coefficient and the Prandtl number is replaced by the Schmidt number. According to Eckert and Drake, the above relationship has been verified by experiments for flow through a tube and flow over a flat plate. The Schmidt number is a dimensionless relationship and is

$$S_c = \frac{\nu}{D} \qquad (64)$$

where

D = diffusion coefficient.

From the above relationships,

$$h_{Dx} = \frac{0.0288 \ D \ S_c^{1/3}}{x} \left(\frac{U_\infty x}{\nu}\right)^{0.80} \qquad (65)$$

where

h_{Dx} = local mass transfer coefficient.

Equation 65 for mass transfer is similar to Equation 49 for heat transfer. Following the same development as for heat transfer, the mean mass transfer coefficient, $\overline{h}_D$, is

$$\overline{h}_D = \frac{0.0289}{z_i^{0.111}} \ D \ S_c^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} L^{0.889} . \qquad (66)$$

The total mass transfer from a reservoir, according to Eckert and Drake (1959), can be written as

$$dM = \frac{\overline{h}_p}{R_1 T} (e_o - e_a) \ dA \qquad (67)$$

where

R_1 = gas constant for water vapor

T = absolute temperature of the water surface

e_o = saturated vapor pressure at the water surface temperature

e_a = vapor pressure of the air.

As Equations 56 and 66 involve the same numerical constants and exponents, the average mass transfer per unit area, $\overline{M}$, for a circular reservoir is

$$\overline{M} = \frac{0.0273 \quad D}{z_i^{0.111} \; R_1 \; T} \; S_c^{1/3} \left(\frac{u_i}{\nu}\right)^{0.778} R^{-0.11} \; (e_o - e_a), \qquad (68)$$

The restrictions for Equation 68 are the same as for Equation 63; namely, that the velocity profile can be approximated by a power law with $p = 7$ and that the Reynolds number does not exceed 10^7.

Mass Transfer from Treated Reservoir

Langmuir and Schaefer (1943) suggested that, by analogy with Ohm's law, evaporation can be expressed by an equation of the type, evaporation rate equals driving force over resistance. The average mass transfer per unit area from an untreated reservoir can be written

$$\overline{M} = \frac{\dfrac{e_o - e_a}{z_i^{0.111} \; R_1 \; T}}{0.0273 \, D \, S_c^{1/3} \left(\dfrac{u_i}{\nu}\right)^{0.778} R^{-0.11}} \qquad (69)$$

If the denominator is set equal to R_a, Equation 69 becomes

$$\overline{M} = \frac{e_o - e_a}{R_a} \qquad (70)$$

which is of the same form as Ohm's law. The term R_a can be designated the resistance to mass transfer through the air overlying the reservoir.

When a monolayer is spread on a reservoir, an additional resistance to evaporation is present. Langmuir and Schaefer (1943) concluded that the presence of the film does not affect diffusion through the overlying air but adds a resistance characteristic of the film itself. The film resistance is in series with the air resistance. Mysel (1959) agreed that the resistances are in series and reported that the driving force for mass transfer is $(e_o - e_a)$. Thus, the average mass transfer rate from a treated reservoir, $\overline{M}_T$, is

$$\overline{M}_T = \frac{e_o - e_a}{R_a + R_f} \tag{71}$$

where

R_f = resistance of the monolayer.

Archer and LaMer (1955) determined the effect of monomolecular films on evaporation in the laboratory. They concluded that, for film pressures of 12 to 25 dynes per square centimeter, the resistance of a monolayer to evaporation, r, is

$$\log r = A + \frac{B}{T} \tag{72}$$

where

r = the reciprocal of evaporation

A and B = constants for a given monolayer

T = surface temperature.

The resistance of a film to evaporation on a reservoir should be a function of wind velocity which may affect film pressure. Therefore, this writer has concluded that

$$R_f = f(U, T) \tag{73}$$

where

R_f = resistance of the monolayer to evaporation

U = wind velocity

T = temperature of the water surface.

The relationship for the film resistance must be determined for each monolayer forming chemical.

CHAPTER IV

FACILITIES, INSTRUMENTATION AND PROCEDURES

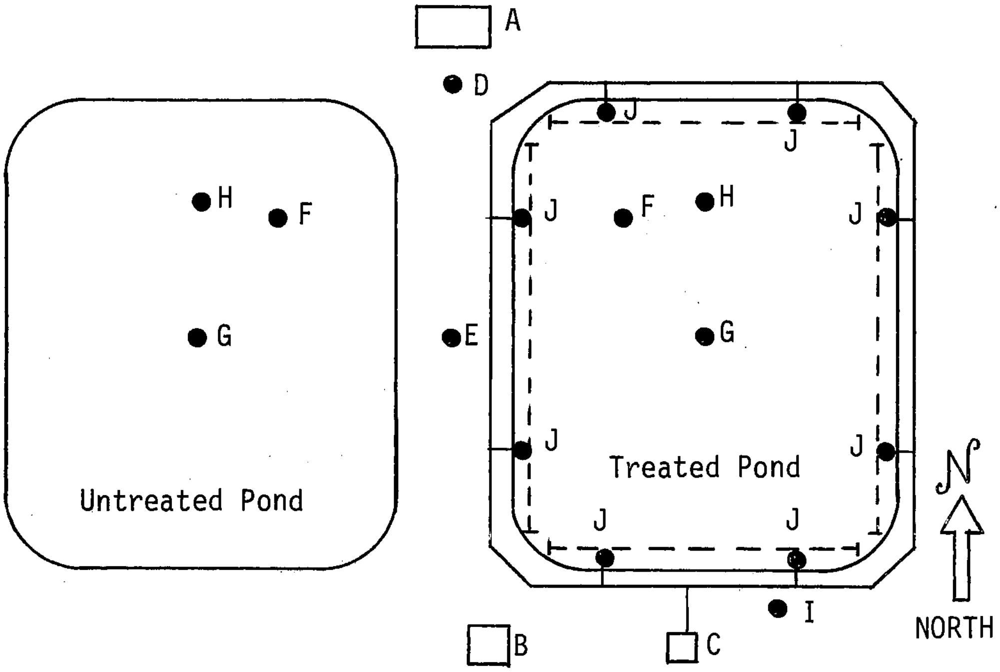
An evaporation and evaporation suppression investigation was conducted on two adjacent ponds at Stillwater, Oklahoma, in 1965. The ponds were as similar as possible with normal construction methods. One pond was treated with a monolayer and the other served as a check. Evaporation was measured for the period August 13 to October 23.

Concurrent measurements were made of all parameters necessary to calculate evaporation by water budget, mass transfer and energy budget methods. The parameters measured included:

1. Water surface elevation of the ponds
2. Precipitation
3. Wind speed
4. Wet and dry bulb temperatures of the air
5. Water surface temperatures of the ponds
6. Total incoming radiation
7. Pond temperature profile.

Figure 2 shows the location of the instruments with respect to the ponds.

Recording instruments were housed in an air-conditioned trailer located at the north side of the ponds as shown in Figure 3. The trailer was adjacent to the sensing instruments and had little



Legend

A. Instrument trailer

B. Gage House for Water Level Recorders

C. Slurry Mixing and Distribution Pump

D. Ventilated Psychrometer & Radiometer

E. Anemometer

F. Thermal Profile Station

G. Water Surface Temperature Station

H. Net Radiometers

I. Wind Vane

J. Solenoid Valves

— — — — — — — —Perforated Plastic Hose

————————Slurry Distribution Line

Figure 2. Plan View of Experimental Pond Site.

Figure 3. Experimental Pond Site Viewed from South Side of Treated Pond.

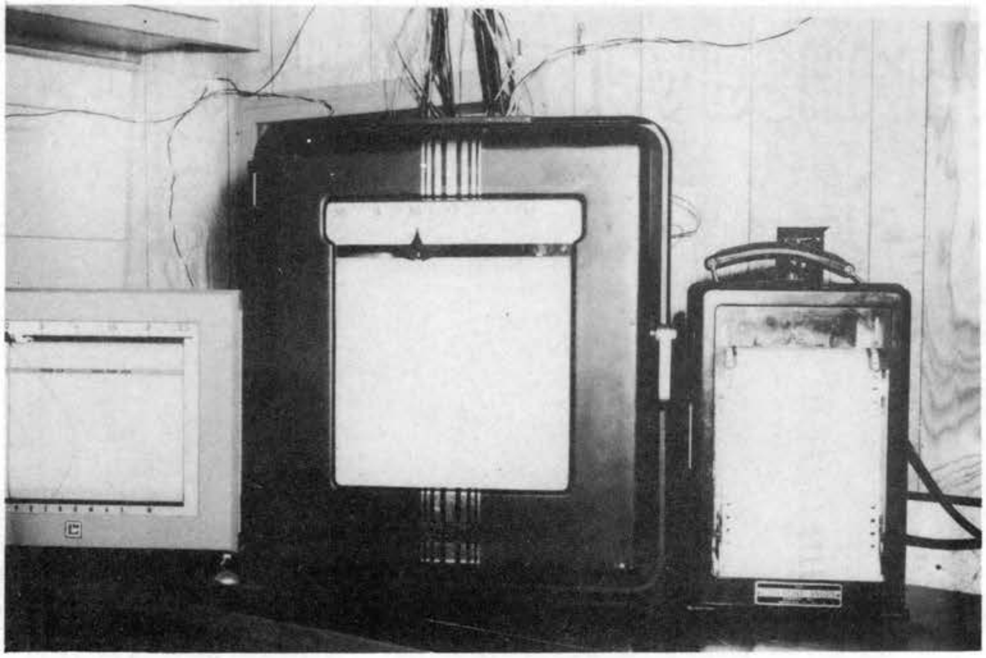


Figure 4. Radiation, Temperature and Wind Travel Recorders.

influence on wind profiles over the ponds as north winds were rare during the study. Figure 4 shows recording instruments inside the trailer.

Experimental Ponds

The two experimental ponds were located on the crest of a ridge at the northwest corner of the Oklahoma State University campus. Dikes diverted runoff from the adjacent area around the ponds. The ponds were 120 feet long, 100 feet wide and 6 feet deep. The earthen banks had a 3 to 1 slope. To prevent seepage, the ponds were lined with a continuous layer of 8 mil polyvinyl chloride which was covered with an earth blanket. The edges of the earth blanket were covered with sheets of polyvinyl to prevent evaporation from the banks.

Water was supplied to the ponds by a University water line. The water level was allowed to drop a maximum of 6 inches before the ponds were refilled during the test period.

Before the evaporation tests were initiated, the ponds were drained and refilled to establish stage-storage curves. One-inch Neptune water meters were installed in the lines supplying water to the ponds. The meters were calibrated volumetrically in place and found to have an error of less than 0.5 percent.

At 8-hour intervals during filling of each pond, the water level was measured with a hook gage, and the volume of water to effect the rise was read from the water meter. The evaporation during this time interval from the full adjacent pond was measured with a point gage. The true rise in stage for an 8-hour period for the measured volume of inflow was the measured rise in stage plus evaporation. An approximation of the average area during the time interval was found by dividing volume of inflow by measured rise in stage. The volume of water evaporated was the product of average area and measured evaporation. This quantity subtracted from measured inflow gave the corrected volume of water in the pond for the measured rise.

Stage-volume equations were developed for the ponds by fitting a fourth degree polynomial to the data. The resulting equations were

$$V_t = -2099.8557 + 4257.6785\ St + 734.8737\ St^2 - 64.4533\ St^3 + 6.2229\ St^4 \tag{74}$$

and

$$V_u = -849.8245 + 1397.7173\ St + 1824.9051\ St^2 - 261.3151\ St^3 + 17.0667\ St^4 \tag{75}$$

where

V_t = volume of treated pond, ft^3

V_u = volume of untreated pond, ft^3

St = water stage, ft

Stage-area equations were obtained by taking the first derivative of the volume with respect to the stage. These equations were

$$A_t = 4257.6785 + 1469.7475\ St - 193.3599\ St^2 + 24.8914\ St^3 \tag{76}$$

and

$$A_u = 1397.7173 + 3649.8102\ St - 783.9454\ St^2 + 68.2666\ St^3 \tag{77}$$

where

A_t = area of treated pond, ft^2

A_u = area of untreated pond, ft^2

St = water stage, ft

Area and volume of the ponds at various stages as calculated by the polynomial equations are given in Table I.

TABLE I

STAGE-AREA-VOLUME FOR EXPERIMENTAL PONDS

Stage ft	Treated Pond Area ft^2	Treated Pond Volume ft^3	Untreated Pond Area ft^2	Untreated Pond Volume ft^3
0.41	--	--	-0-	-0-
0.46	-0-	-0-	--	--
0.50	4947	205	3035	274
1.00	5559	2834	4332	2129
1.50	6111	5961	5339	4557
2.00	6623	8939	6108	7428
2.50	7112	12373	6689	10634
3.00	7599	16051	7135	14094
3.50	8100	19975	7496	17754
4.00	8636	24157	7823	21584
4.50	9224	28619	8168	25580
5.00	9884	33393	8581	29764
5.50	10633	38518	9115	34182
6.00	11492	44045	9820	38907
6.50	12477	50031	10748	44039

A short calibration test was run at the beginning of the investigation to determine if the ponds were evaporating at the same rate. The check pond lost 0.01 inch per day more than the pond to be treated. The loss was assumed to be due to seepage and evaporation from the untreated pond was corrected by this amount in the analysis of the data.

Chemical Mixing and Distribution System

A mixing and distribution system similar to that used by Crow (1961) was installed to apply monolayer forming chemicals to the treated pond. Powdered chemical was added to water and continuously, mechanically stirred in a mixing barrel. The resulting slurry was delivered to the intake side of an electric driven pump which circulated pond water through the distribution system. Metering of the slurry was controlled by a solenoid valve and anemometer. The valve was activated after each 0.1 mile of wind travel and was held open a pre-set time interval by an automatic reset timer. The slurry mixing tank and metering devices are shown in Figure 5.

Water drawn from beneath the surface of the pond was continuously circulated through a distribution line laid around the pond. The water served to dilute and transport the slurry to the pond. A plastic hose, with holes at 5-foot intervals, was laid beneath the water surface along each side of the pond. The perforated plastic hose was laid with the openings up and bubbled the monolayer forming solution to the surface. The plastic hose along each side of the pond was capped at the ends and was connected to the distribution line through two normally closed solenoid valves. The location of the solenoid valves is shown in Figure 2.

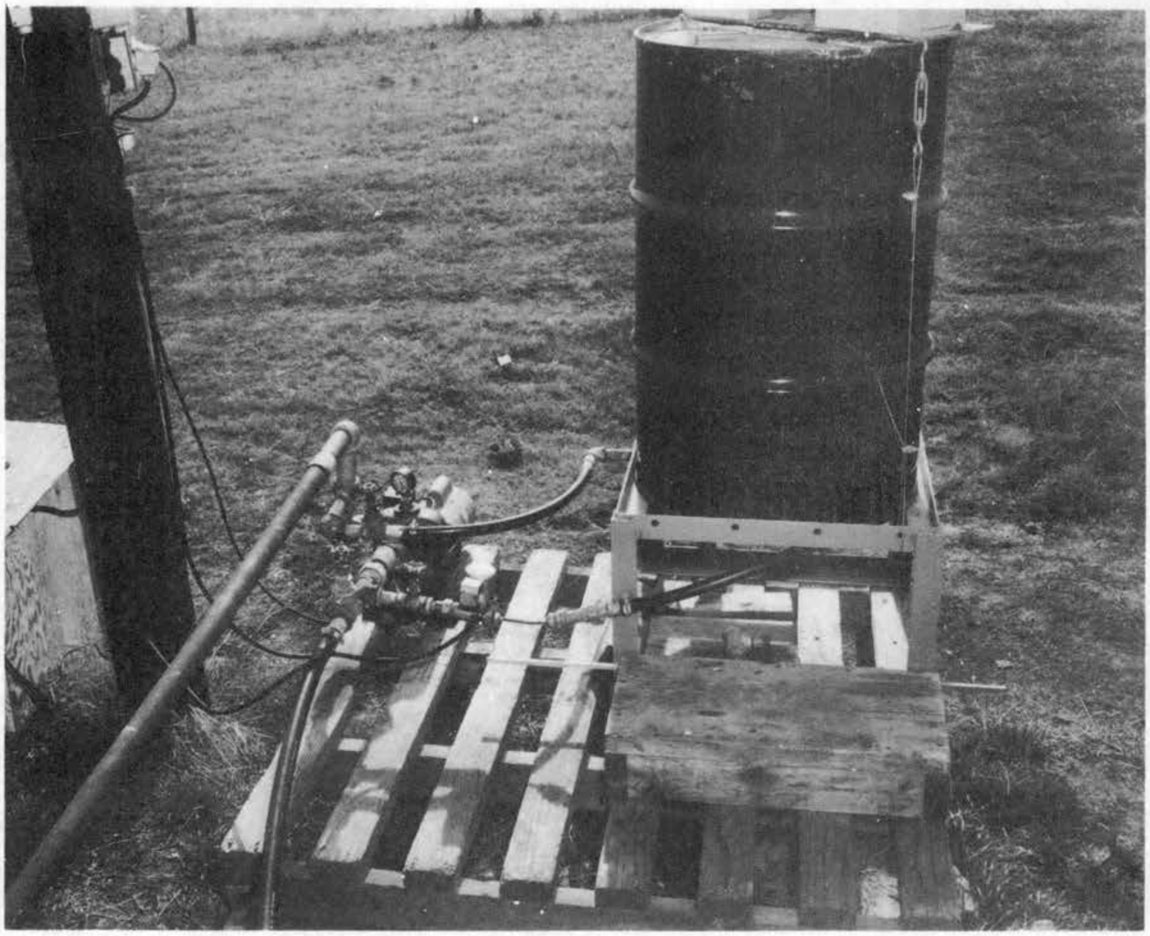


Figure 5. Slurry Mixing Tank, Pump and Metering Devices.

A wind vane with eight contact points activated the solenoid valves. Two contact points were closed at any instant opening the two upwind solenoid valves. The slurry carrying water passed through these two open valves. Thus monolayer forming solution was delivered to two sides of the pond except when the wind was from due north, east, south or west. Then the two valves on that side were open and monolayer forming solution was applied from one side. Figure 6 shows a portion of the distribution system bubbling monolayer solution to the pond surface.

The monolayer forming chemical was in powdered form and of the following chemical analysis: 2 percent C_{14}, 29 percent C_{16}, 61 percent C_{18}, 5 percent C_{20} and 3 percent non-alcohol.

The slurry normally consisted of 3 pounds of chemical mixed with 50 gallons of water. The strength of slurry and time interval during which the slurry was injected into the distribution system were determined by visual inspection of film cover. Sufficient chemical was applied to maintain a continuous film cover on the pond. The rate of chemical applied to the treated pond varied with wind speed and temperature. Daily application rates ranged from 4 pounds for average wind speed of 3 miles per hour to 33 pounds for average wind speed of 13 miles per hour.

Precipitation

Rainfall was measured with a standard Weather Bureau rain gage. The rain gage was located south of the ponds in an area exposed to normal wind patterns.

Figure 6. Slurry Distribution System Delivering Monolayer Forming Solution to the Pond Surface.

Water Surface Elevations

Water surface elevations were measured in a stilling well, located in a small building on the south side of the ponds, connected to each pond with a 1 1/2-inch diameter plastic pipe. A 1/8-inch diameter copper tube was inserted in each line at the entrance to the stilling wells to dampen surges into the wells caused by wave action on the ponds. The water level in the ponds was continuously recorded by Stevens Type F stage recorders mounted over the stilling wells. The water levels were also measured at approximately 8 a.m. and 8 p.m. each day with laboratory type point gages in the stilling wells.

Wind Travel

Wind travel was measured by a Bendix-Friez totalizing cup anemometer set 2 meters above the mean water surface elevation. This anemometer also controlled the frequency of slurry injection into the chemical distribution system.

Wind travel was continuously recorded by an event marker adapted from an Esterline-Angus recording watt-hour meter. After each 0.9 mile of wind travel, a circuit containing a light bulb was closed for 0.1 mile of wind travel. The closed circuit provided a break in the line traced by the recording pen on the strip chart. Wind travel was also read at approximately 8 a.m. and 8 p.m. from the totalizing register on the anemometer.

Air Temperatures

Vapor pressure of the air was computed from temperatures measured by a dry and wet bulb psychrometer as shown in Figure 7. The

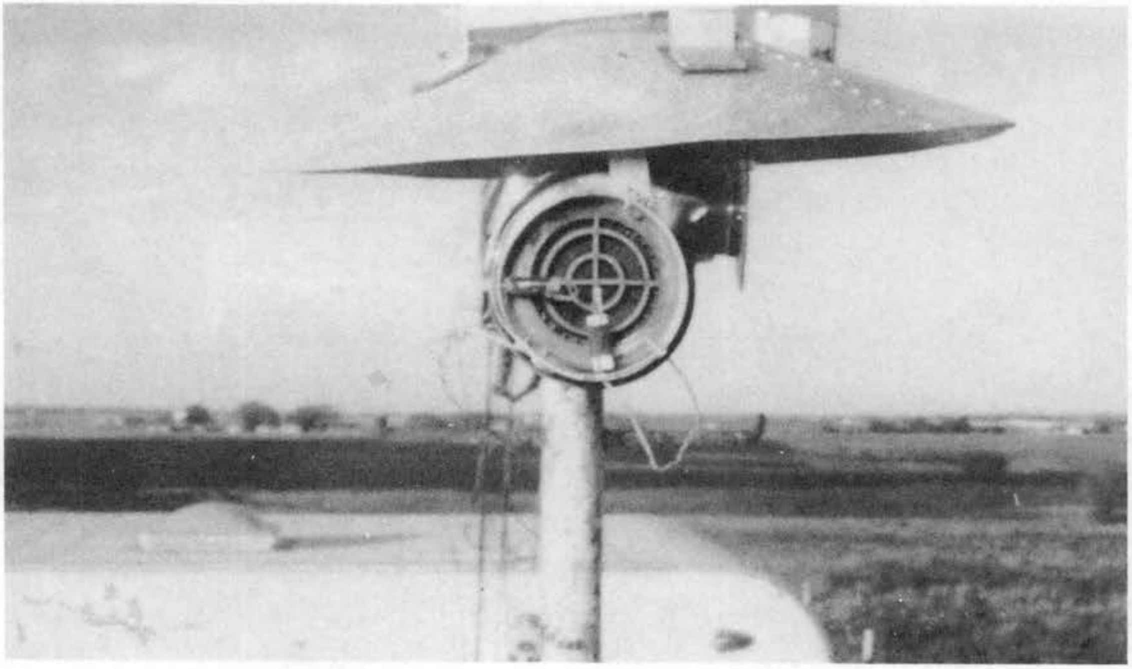


Figure 7. Ventilated Psychrometer for Measuring Wet and Dry Bulb Temperatures.

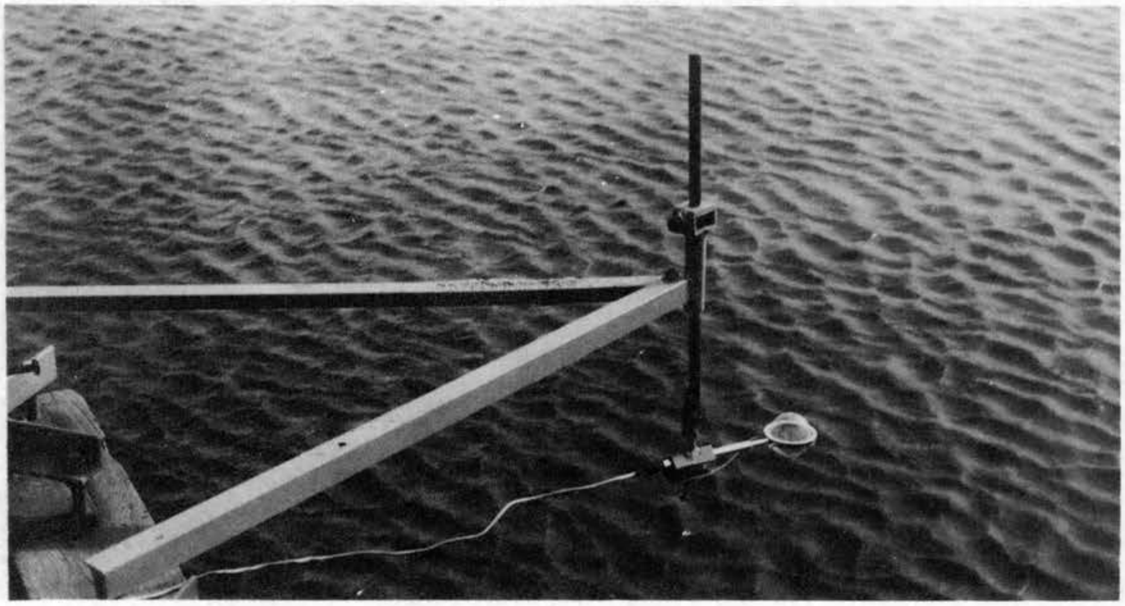


Figure 8. Miniature Net Radiometer Mounted 18 Inches Above Untreated Pond.

psychrometer was mounted 2 meters above the mean water surface elevation. A one-fortieth horsepower electric fan ventilated the thermocouples. Water from a bottle was supplied to the wet thermocouple through a wick. Temperatures were recorded at 7.68-minute intervals by a Leeds and Northrup Speedomax G multipoint recorder.

Water Surface Temperatures

Water surface temperature was measured with a thermocouple located at the center of each pond. The thermocouple was attached firmly to the bottom of a 2-inch thick styrofoam float. Thus the water temperature was measured at a depth of approximately one-half inch. The water surface temperatures were recorded at 7.68-minute intervals by a Leeds and Northrup Speedomax G multipoint recorder.

Total Incoming Radiation

Total incoming hemispherical radiation was detected by a Beckman and Whitley ventilated thermal radiometer. The radiometer was mounted on a mast 13 feet above the ground. Output of the radiometer was recorded by a self-balancing Leeds and Northrup Speedomax W multipoint recorder. A voltage divider was built into the circuit so that radiation was recorded in langleys per minute. Radiation was recorded every 40 seconds giving a continuous trace on the strip chart driven at one inch per hour.

A thermocouple, mounted in the surface, detected the temperature of the flat plate radiometer surface. The temperature was recorded by a Leeds and Northrup Speedomax G multipoint recorder every 7.68 minutes.

Net Radiation

A model 605 miniature net radiometer, built by C. W. Thornwaite Associates, was mounted over both the treated and untreated pond. The net radiometers were mounted on an adjustable stand and maintained at a height of 18 to 19 inches above the water surface as shown in Figure 8. Output from the net radiometers was recorded each 40 seconds by a Leeds and Northrup Speedomax multipoint recorder.

Water Temperature Profiles

Energy storage in the ponds was computed from a thermal profile taken at 8 a.m. and 8 p.m. each day. One thermal profile station was located in each pond as shown in Figure 2. This location provided temperature measurements the full depth of the pond. Thermocouples were located at the surface and at 0.5-, 1-, 2-, 4- and 6-foot depths. Temperatures were obtained with a Leeds and Northrup potentiometer calibrated to read in degrees Fahrenheit.

Performance of Instruments and Equipment

During the course of data collection, there was some malfunctioning of the instruments and of the monolayer distribution system. The wick supplying water to the wet bulb psychrometer occassionally became soiled and had to be replaced. Erroneous readings were discovered by comparing wet bulb temperatures from the recording psychrometer with those taken with a sling psychrometer. Of the 71 days on which vapor pressures of the air were evaluated, accurate data were obtained for 65 days. The solenoid valve supplying slurry from the mixing barrel into the distribution system became clogged and was inoperative for two of the 53 days that a monolayer was applied to the treated pond. Minor difficulties were encountered with the flat plate radiometer. Six days of data were lost during the 71 days that radiation was measured. The Thornthwaite net radiometer proved to be fragile. One of the two net radiometers was returned to the factory for repairs after two weeks of operation. However, the net radiometers are relatively inexpensive and a spare unit could be kept for use when one becomes inoperative.

Usuable Data

Those days with errors in the measurement of evaporation parameters were not included in the analysis of data. Also, any day with rainfall was omitted to eliminate rainfall as a parameter. Data for the treated pond were excluded on those days during which a complete film was not maintained. As a result, evaporation parameters required to estimate evaporation by mass transfer equations were evaluated on 51 days for the untreated pond and on 33 days for the treated pond. Parameters necessary to estimate evaporation by the energy budget were evaluated on 45 days for the untreated pond and 31 days for the treated pond.

CHAPTER V

EVAPORATION PARAMETERS

Introduction

Water budget evaporation was determined directly from changes in water surface elevation. This was possible because the ponds were lined to prevent seepage and there was no inflow or outflow. On the other hand, evaporation by the mass transfer and energy budget methods was determined indirectly by evaluating evaporation parameters. The radiation parameters were measured directly. Other parameters, such as properties of the air and vapor pressures, were evaluated by standard equations from air and water temperatures. This chapter includes the equations used to evaluate the evaporation parameters and the numerical values of the parameters.

Evaporation was determined on a daily basis. A test day began at 8:00 p.m. and was identified by the date of the daylight hours during the 24-hour period. Thus a test day which began at 8:00 p.m. on August 14 and ended at 8:00 p.m. on August 15 was dated August 15.

Average daily values of the evaporation parameters were used for daily evaporation calculations by the mass transfer method. For the energy budget, daily values of the energy parameters were the summation of quantities recorded during the test day.

Evaporation parameters were measured and recorded in both the metric and English system of measurements, depending on the instruments available. However, all calculations were performed and data presented in the metric system.

Wind Velocity

Wind travel was recorded on strip charts as miles traveled by the anemometer. The distance of wind travel each hour or average hourly wind velocity is given in Appendix A. Daily wind velocity, U, was taken as the average of the hourly wind velocities and is given in Table II.

Atmospheric Pressure

From the Smithsonian Meteorological Tables (1951), it was determined that standard atmospheric pressure, P, for the elevation at the ponds is 980 millibars. Daily atmospheric pressure measured at the weather station on the Oklahoma State University campus ranged from 968 to 991 millibars during the study. Changes of this magnitude had no significant effect on the evaporation parameters. Thus, atmospheric pressure was assumed to be constant at 980 millibars.

Air and Pond Surface Temperatures

All temperatures were recorded on strip charts at 7.68-minute intervals. The temperature readings were read from the strip charts and entered onto computer cards. Weighted average hourly temperatures were calculated by computer. Appendix B gives average hourly dry bulb and wet bulb temperatures of the air 2 meters above the water surface. Average hourly water surface temperatures for the treated and untreated ponds are given in Appendix C.

TABLE II

DAILY WIND SPEED AND AIR TEMPERATURE, 1965

Date	Wind Speed U cm/sec	Air Temperature	
		Dry Bulb	Wet Bulb
		T_a	T_w
		^{o}C	^{o}C
8/14	317.40	26.56	21.23
8/15	225.57	24.68	20.57
8/16	294.49	24.13	20.67
8/17	343.85	27.57	22.23
8/18	377.56	29.51	21.69
8/19	371.97	27.00	22.14
8/21	157.40	26.95	22.11
8/24	241.03	26.76	22.99
8/25	361.17	29.23	23.43
8/26	481.13	31.09	23.81
8/27	389.48	29.88	23.06
8/28	280.15	24.10	20.82
8/29	368.44	25.82	21.37
8/30	521.17	28.57	22.84
9/1	209.92	19.19	15.30
9/2	316.09	21.03	16.49
9/5	353.35	27.07	23.03
9/9	312.74	27.65	22.63
9/10	396.38	25.12	21.41
9/14	359.68	31.58	21.52
9/15	466.97	28.53	21.47
9/16	593.26	29.61	21.72
9/23	314.98	16.59	13.51
9/24	229.29	12.12	9.29
9/25	228.55	14.29	11.78
9/26	265.80	18.42	16.10
9/27	324.10	19.41	16.28
9/28	303.06	20.05	16.60
9/29	370.48	21.23	18.28
9/30	521.55	13.17	11.12
10/1	137.84	13.07	9.87
10/2	133.55	14.64	11.09
10/3	87.36	14.94	12.74
10/4	113.25	16.37	14.28
10/5	161.31	15.14	12.69
10/6	207.87	14.36	12.54
10/7	326.15	18.84	14.73
10/8	122.75	18.59	14.38
10/9	167.64	20.90	15.89
10/10	162.80	21.57	16.29
10/12	156.65	12.04	7.80
10/13	237.49	18.79	14.91
10/14	416.68	21.26	18.35
10/15	312.00	21.16	18.50
10/16	399.91	22.86	20.08
10/17	382.03	22.27	19.23
10/19	255.93	18.30	16.01
10/20	302.50	14.29	11.24
10/21	495.47	11.86	8.79
10/22	284.43	10.93	6.94
10/23	269.90	14.74	11.03

Daily temperatures were taken as an average of the hourly temperatures. Table II gives daily wet bulb temperature, T_w, and daily dry bulb temperature, T_a, of the air. Daily water surface temperatures, T_o, are given in Tables III and IV for the treated and untreated ponds, respectively.

Vapor Pressures

The vapor pressure at the pond surface was taken as the vapor pressure of saturated air at the water surface temperature. The vapor pressure was calculated by the equation presented by Runkles and others (1964)

$$e_o = 5.979 + 0.5183\ T_o + 0.005630\ T_o^2 + 0.0005890\ T_o^3 \qquad (78)$$

where

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

T_o = daily water surface temperature, °C.

This equation was obtained by fitting a cubic equation to the vapor pressure tables in the Smithsonian Meteorological Tables.

The vapor pressure of the air was determined from wet and dry bulb temperatures measured at a height of 2 meters. The vapor pressure was calculated by the equation given in the Smithsonian Meteorological Tables (1951)

$$e_a = e_s - [0.000660\ (1.0 + 0.00115\ T_w)]\ P\ (T_a - T_w) \qquad (79)$$

where

e_a = daily vapor pressure of the air, mb

TABLE III

DAILY POND SURFACE TEMPERATURES AND PROPERTIES OF THE AIR FOR THE TREATED POND, 1965

Date	Pond Surface Temperature T_o ^{o}C	Vapor Pressure Deficit Δe mb	Kinematic Viscosity ν_2 $\frac{cm^2}{sec}$	Diffusivity D_2 $\frac{cm^2}{sec}$	Schmidt Number Sc -	Thermal Conductivity k $\frac{cal}{cm\text{-}sec\text{-}^{o}C}$
8/14	26.54	13.09	0.1643	0.2727	0.6024	0.00006251
8/15	27.10	14.44	0.1637	0.2716	0.6026	0.00006240
8/16	27.38	14.48	0.1636	0.2714	0.6027	0.00006238
8/17	28.55	15.86	0.1660	0.2752	0.6031	0.00006276
8/18	29.49	20.55	0.1674	0.2776	0.6029	0.00006299
8/19	30.19	19.57	0.1666	0.2761	0.6035	0.00006284
8/21	30.57	20.56	0.1668	0.2764	0.6036	0.00006287
8/24	31.55	20.92	0.1673	0.2770	0.6041	0.00006294
8/25	31.24	20.69	0.1684	0.2788	0.6039	0.00006311
8/26	30.50	19.11	0.1689	0.2798	0.6036	0.00006320
8/27	30.21	19.39	0.1681	0.2785	0.6035	0.00006308
8/28	30.18	20.58	0.1651	0.2737	0.6034	0.00006261
8/29	30.05	20.20	0.1659	0.2750	0.6033	0.00006274
8/30	29.42	17.12	0.1670	0.2768	0.6033	0.00006291
9/1	26.15	19.15	0.1602	0.2664	0.6016	0.00006187

TABLE III (Continued)

Date	Pond Surface Temperature T_o °C	Vapor Pressure Deficit Δe mb	Kinematic Viscosity ν $\frac{cm^2}{sec}$	Diffusivity D $\frac{cm^2}{sec}$	Schmidt Number Sc -	Thermal Conductivity k $\frac{cal}{cm\text{-}sec\text{-}^oC}$
9/2	26.03	17.95	0.1611	0.2678	0.6017	0.00006201
9/9	30.23	18.98	0.1670	0.2767	0.6036	0.00006290
9/10	29.59	18.54	0.1653	0.2741	0.6033	0.00006264
9/14	28.48	19.98	0.1678	0.2785	0.6024	0.00006308
9/15	28.33	17.72	0.1662	0.2758	0.6027	0.00006282
9/16	27.27	15.54	0.1662	0.2759	0.6024	0.00006282
9/24	19.96	13.34	0.1534	0.2557	0.6000	0.00006077
9/25	19.11	9.88	0.1541	0.2567	0.6002	0.00006088
9/26	19.67	6.13	0.1565	0.2605	0.6008	0.00006127
9/27	20.11	7.09	0.1572	0.2616	0.6008	0.00006139
9/28	21.02	8.27	0.1580	0.2629	0.6009	0.00006152
9/29	21.73	6.96	0.1590	0.2644	0.6013	0.00006168
9/30	20.58	12.26	0.1543	0.2570	0.6003	0.00006091
10/1	19.19	12.05	0.1535	0.2558	0.6000	0.00006079
10/2	19.73	12.02	0.1545	0.2575	0.6001	0.00006096
10/3	19.69	9.60	0.1547	0.2577	0.6004	0.00006098
10/4	19.60	7.87	0.1554	0.2588	0.6006	0.00006110
10/5	19.72	9.85	0.1548	0.2579	0.6004	0.00006100

TABLE IV

DAILY POND SURFACE TEMPERATURES AND PROPERTIES OF THE AIR FOR THE UNTREATED POND, 1965

Date	Pond Surface Temperature T_o ^oC	Vapor Pressure Deficit Δe mb	Kinematic Viscosity ν $\frac{cm^2}{sec}$	Diffusivity D $\frac{cm^2}{sec}$	Schmidt Number Sc -	Thermal Conductivity k $\frac{cal}{cm\text{-}sec\text{-}^oC}$
8/14	25.52	11.03	0.1637	0.2719	0.6022	0.00006243
8/15	25.54	11.26	0.1628	0.2704	0.6022	0.00006227
8/16	25.35	10.33	0.1625	0.2698	0.6023	0.00006221
8/17	25.83	10.06	0.1644	0.2730	0.6024	0.00006254
8/18	25.89	12.68	0.1653	0.2746	0.6021	0.00006270
8/19	26.78	11.84	0.1647	0.1647	0.2733	0.00006257
8/21	27.74	13.90	0.1652	0.2740	0.6029	0.00006264
8/24	28.76	14.03	0.1658	0.2747	0.6034	0.00006271
8/25	28.18	13.29	0.1666	0.2763	0.6031	0.00006286
8/26	27.69	12.51	0.1673	0.2774	0.6029	0.00006297
8/27	27.24	12.57	0.1664	0.2761	0.6027	0.00006284
8/28	27.08	13.48	0.1634	0.2711	0.6027	0.00006235
8/29	26.81	12.85	0.1641	0.2723	0.6026	0.00006247
8/30	26.59	10.84	0.1654	0.2744	0.6027	0.00006268
9/1	23.82	14.70	0.1590	0.2645	0.6012	0.00006168
9/2	23.57	13.31	0.1598	0.2658	0.6012	0.00006181
9/5	25.97	8.15	0.1643	0.2727	0.6027	0.00006251

TABLE IV (Continued)

Date	Pond Surface Temperature T_o ^oC	Vapor Pressure Deficit Δe mb	Kinematic Viscosity ν $\frac{cm^2}{sec}$	Diffusivity D $\frac{cm^2}{sec}$	Schmidt Number Sc -	Thermal Conductivity k $\frac{cal}{cm\text{-}sec\text{-}^oC}$
9/9	27.19	11.97	0.1653	0.2742	0.6028	0.00006265
9/10	26.43	11.51	0.1636	0.2715	0.6026	0.00006238
9/14	25.31	13.33	0.1660	0.2759	0.6017	0.00006282
9/15	25.15	11.11	0.1645	0.2732	0.6020	0.00006256
9/16	24.32	9.70	0.1645	0.2734	0.6017	0.00006258
9/23	21.37	11.92	0.1564	0.2604	0.6006	0.00006126
9/24	18.37	11.15	0.1526	0.2544	0.5998	0.00006064
9/25	17.39	7.62	0.1532	0.2553	0.6000	0.00006074
9/26	18.10	3.98	0.1557	0.2592	0.6006	0.00006114
9/27	18.71	5.12	0.1565	0.2605	0.6006	0.00006127
9/28	19.53	6.08	0.1572	0.2617	0.6007	0.00006140
9/29	20.37	4.87	0.1583	0.2633	0.6011	0.00006156
9/30	19.06	10.07	0.1535	0.2558	0.6002	0.00006078
10/1	16.97	9.17	0.1523	0.2540	0.5997	0.00006060
10/2	17.50	9.04	0.1534	0.2557	0.5999	0.00006078
10/3	17.66	6.87	0.1537	0.2561	0.6002	0.00006082
10/4	17.74	5.36	0.1545	0.2573	0.6003	0.00006094
10/5	17.95	7.44	0.1539	0.2565	0.6002	0.00006086
10/6	17.59	6.72	0.1534	0.2556	0.6002	0.00006076
10/7	17.82	6.32	0.1557	0.2593	0.6002	0.00006115
10/8	18.64	7.84	0.1559	0.2598	0.6003	0.00006120
10/9	19.26	7.56	0.1574	0.2622	0.6004	0.00006144
10/10	19.90	8.19	0.1581	0.2632	0.6006	0.00006155
10/12	16.60	10.95	0.1516	0.2529	0.5994	0.00006049
10/13	17.43	5.49	0.1554	0.2590	0.6002	0.00006112

TABLE IV (Continued)

Date	Pond Surface Temperature T_o ^oC	Vapor Pressure Deficit Δe mb	Kinematic Viscosity ν $\frac{cm^2}{sec}$	Diffusivity D $\frac{cm^2}{sec}$	Schmidt Number Sc -	Thermal Conductivity k $\frac{cal}{cm\text{-}sec\text{-}^oC}$
10/14	18.47	2.08	0.1573	0.2618	0.6008	0.00006141
10/15	19.51	3.14	0.1578	0.2626	0.6010	0.00006149
10/16	20.33	2.21	0.1591	0.2646	0.6014	0.00006169
10/17	20.78	4.25	0.1590	0.2645	0.6013	0.00006168
10/19	19.22	5.57	0.1562	0.2600	0.6007	0.00006123
10/20	18.41	9.75	0.1537	0.2562	0.6000	0.00006082
10/21	16.13	8.91	0.1513	0.2524	0.5995	0.00006043
10/22	13.80	8.31	0.1497	0.2498	0.5991	0.00006016
10/23	14.13	5.34	0.1517	0.2531	0.5995	0.00006050

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

T_w = daily wet bulb temperature, °C

P = daily atmospheric pressure, mb

T_a = daily dry bulb temperature, °C.

The driving force for evaporation is the difference between the vapor pressure of saturated air at the temperature of the water surface and the vapor pressure of the air at 2 meters. Daily vapor pressure deficit, Δe, is given in Tables III and IV for the treated and untreated pond, respectively.

Kinematic Viscosity

According to the Smithsonian Meteorological Tables (1951), the dynamic viscosity of air is independent of pressure except at very low pressures. Its temperature dependence is expressed by the equation

$$\frac{\mu}{\mu_o} = \frac{T_o + C}{T + C} \left(\frac{T}{T_o}\right)^{1.5} \tag{80}$$

where

μ = dynamic viscosity of air, g/cm-sec

μ_o = known dynamic viscosity, g/cm-sec

T_o = temperature at which μ_o is known, °K

T = temperature, °K

C = a constant, 120°C

Birge (1945) reported that $\mu_o = 0.00018325 \pm 0.00000010$ grams per centimeter per second at $T_o = 296.16$ degrees Kelvin.

The dynamic viscosity of the air at the pond surface was different from that at a height of 2 meters due to a difference in temperature. Daily dynamic viscosity of the air at the pond surface and at 2 meters was calculated by the equation

$$\mu = 0.00018325 \left(\frac{416.16}{T + 120.0}\right)\left(\frac{T}{296.16}\right)^{1.5} \qquad (81)$$

where

μ = daily dynamic viscosity, g/cm-sec

T = daily temperature, °K

by substituting in the appropriate temperature. Daily dynamic viscosity of the air, μ, was taken as the arithmetic average of the viscosities at the two levels.

The density of moist air is equal to the mass of dry air plus the mass of water vapor per unit volume. Linsley and others (1958) reported that

$$\rho = \frac{P}{RT}\left(1.0 - 0.378\,\frac{e}{P}\right)$$

where

ρ = density of moist air, g/cm^3

P = atmospheric pressure, mb

R = gas constant, 2870.4 cm^3-mb/g-K

T = air temperature, °K

e = vapor pressure of the air, mb.

The daily density of air at the pond surface and at 2 meters was calculated by the above equation using the appropriate temperatures and vapor pressures. Daily air density, ρ, was taken as the arithmetic average at the two levels.

Kinematic viscosity is the ratio of the dynamic viscosity to the density. Daily kinematic viscosity of the air above the ponds, ν, is given in Tables III and IV for the treated and untreated ponds, respectively.

Diffusivity

According to the Smithsonian Meteorological Tables (1951), the dependence of the diffusivity of water vapor in air on temperature and pressure is expressed by the equation

$$\frac{D}{D_o} = \left(\frac{T}{T_o}\right)^n \left(\frac{P_o}{P}\right) \tag{83}$$

where

D = diffusivity of water vapor in air, cm^2/sec

D_o = known diffusivity of water vapor in air, cm^2/sec

T = temperature of air, °K

T_o = temperature at which D_o is known, °K

P_o = atmospheric pressure at which D_o is known, mb

P = atmospheric pressure, mb.

The Smithsonian Meteorological Tables reported that $n = 1.81$ and D_o = 0.226 square centimeters per second at a temperature of zero degrees Centigrade and an atmospheric pressure of 1000 millibars.

The air temperature above the ponds for determining diffusivity was taken as the arithmetic average of the pond surface and the dry bulb temperature at 2 meters. Daily diffusivity, D, was calculated from the equation

$$D = 0.226 \left(\frac{T}{296.16}\right)^{1.81} \frac{1000}{P} \tag{84}$$

where

D = daily diffusivity of water vapor in air, cm^2/sec

T = daily air temperature above the pond, °K

P = daily atmospheric pressure, mb.

Tables III and IV gives values of D for the treated and untreated ponds, respectively.

Schmidt Number

The Schmidt number is the ratio of kinematic viscosity to diffusivity. A daily Schmidt number, Sc, was calculated from daily kinematic viscosity and daily diffusivity. Tables III and IV give values of Sc for the treated and untreated ponds, respectively.

Thermal Conductivity

The Smithsonian Meteorological Tables (1951) reported that the thermal conductivity of air at zero degrees Centigrade is 0.000058 calories per centimeter per second per degree Centigrade. Values at other temperatures are assumed proportional to dynamic viscosity. Daily thermal conductivity of the air above the ponds, k, was calculated by the equation

$$k = \frac{0.000058}{0.0001718} \mu \tag{85}$$

where

k = daily thermal conductivity, cal/cm-sec-°C
0.000058 = thermal conductivity at 0°C, cal/cm-sec-°C
μ = daily dynamic viscosity, g/cm-sec
0.0001718 = dynamic viscosity at 0°C.

Values of k for the treated and untreated pond are given in Tables III and IV, respectively.

Prandtl Number

The Prandtl number is a dimensionless term expressed by the equation

$$Pr = \frac{c_p \mu}{k} \tag{41}$$

where

Pr = Prandtl number
c_p = specific heat of air at constant pressure, cal/g-°K
μ = dynamic viscosity, g/cm-sec
k = thermal conductivity, cal/cm-sec-°K.

The Prandtl number for air above the ponds, Pr, had a constant value of 0.7108 for the air temperatures encountered during this study.

Solar Radiation

Solar radiation at the weather station on the Oklahoma State University campus was used in the energy budget. An Eppley pyrheliograph measured and recorded solar radiation. Daily solar radiation, Q_s, in calories per square centimeter is given in Table V.

TABLE V

DAILY INCOMING AND REFLECTED RADIATION FOR TREATED AND UNTREATED PONDS, 1965

Date	Incoming Radiation		Reflected Radiation	
	Solar Q_s cal/cm^2	Atmospheric Q_a cal/cm^2	Solar Q_r cal/cm^2	Atmospheric Q_{ar} cal/cm^2
8/14	536.0	879.2	35.4	26.3
8/15	432.6	912.3	31.6	27.3
8/16	468.1	907.2	33.0	27.2
8/17	574.8	910.6	36.6	27.3
8/18	567.6	934.4	36.4	28.0
8/21	536.1	898.1	35.4	26.9
8/24	554.4	923.6	36.0	27.7
8/25	587.1	929.3	40.5	27.8
8/26	551.4	931.5	35.9	27.9
8/27	487.2	874.8	33.7	26.2
8/28	582.6	813.6	40.3	24.4
8/29	585.2	869.3	40.4	26.0
8/30	576.3	909.3	40.2	27.2
9/1	615.9	738.8	41.3	22.1
9/2	559.5	799.9	39.6	23.9
9/5	533.4	871.9	35.3	26.1
9/9	526.5	895.9	35.0	26.8
9/10	467.7	770.6	32.9	23.1
9/14	415.6	889.8	30.8	26.6
9/15	507.2	848.3	34.4	25.4
9/16	506.1	845.4	37.9	25.3
9/23	306.3	706.2	25.6	21.1
9/24	202.2	741.4	19.1	22.2
9/25	147.0	782.9	14.9	23.4
9/26	364.5	809.2	28.5	24.2
9/27	472.5	743.4	36.7	22.3
9/28	485.4	749.3	37.1	22.4
9/29	462.0	764.1	36.3	22.9
10/1	493.2	626.8	37.4	18.8
10/2	408.0	692.4	30.5	20.7
10/3	190.8	720.9	18.3	21.6
10/4	192.0	798.0	18.4	23.9
10/5	347.7	750.2	27.7	22.5
10/6	325.2	695.2	26.6	20.8
10/7	450.6	623.3	35.8	18.7
10/8	435.0	709.0	35.2	21.2
10/9	438.3	699.8	35.3	20.9
10/10	407.7	739.5	30.5	22.1
10/13	403.2	773.5	30.3	23.2
10/14	242.7	792.0	21.8	23.7
10/15	291.0	797.4	24.7	23.9
10/20	365.7	621.1	28.6	18.6
10/21	408.3	515.4	34.1	15.4
10/22	404.1	552.6	33.9	16.5
10/23	364.8	612.2	28.6	18.3

Atmospheric Radiation

Total incoming radiation, as measured by a flat plate radiometer, is the sum of a back radiation component from the plate and a recorded component. Hourly average plate temperatures were computed from recorded temperatures. Hourly back radiation from the radiometer flat plate was calculated from a form of the Stefan-Boltzman equation

$$E = 60.0\ \sigma\ T^4 \tag{86}$$

where

E = hourly radiation emitted, cal/cm^2
60.0 = minutes per hour
σ = 8.132×10^{-11}, cal/cm^2-min-K^4
T = average hourly temperature of flate plate, °K.

Daily back radiation was a sum of the calculated hourly back radiation.

The recorded radiation component was computed from readings taken from the recorder charts at 12-minute intervals. Hourly radiation was calculated and corrected using average hourly flat plate temperatures. This correction was necessary as the transducer temperature was different from transducer calibration temperature.

Atmospheric radiation is total incoming radiation minus solar radiation. Daily atmospheric radiation, Q_a, is given in Table V.

Reflected Solar Radiation

Reflected solar radiation was computed by the method outlined by Koberg (1964). An equation was fitted to the curve presented by Koberg for clear sky radiation. The equation was

$$Q_{sc} = 741.266 + 2.7247\ E_d - 0.018895\ E_d^{\ 2} - 0.00010389\ E_d^{\ 3} + 0.00000041474\ E_d^{\ 4} \tag{87}$$

where

Q_{sc} = clear sky radiation, cal/cm^2-day

E_d = number of days since April 30.

The ratio of measured solar radiation to calculated clear sky radiation determined cloud cover for the day. If the ratio were equal to or greater than 0.8, the day was classified as clear. For a ratio less than 0.8 the day was classified as cloudy.

Equations were fitted to the reflected solar radiation curves presented by Koberg. The equation for a clear sky was

$$Q_r = 0.70588 + 0.13888\ Q_s - 0.19325 \times 10^{-3}\ Q_s^{\ 2} + 0.15027 \times 10^{-6}\ Q_s^{\ 3} - 0.46334 \times 10^{-10}\ Q_s^{\ 4} \tag{88}$$

and for a cloudy sky the equation was

$$Q_r = 0.57456 + 0.11661 - 0.14142 \times 10^{-3}\ Q_s^{\ 2} + 0.99272 \times 10^{-7}\ Q_s^{\ 3} - 0.28180 \times 10^{-10}\ Q_s^{\ 4} \tag{89}$$

where

Q_r = reflected solar radiation, cal/cm^2-day

Q_s = measured solar radiation, cal/cm^2-day.

Daily reflected solar radiation, Q_r, was calculated by these equations and is given in Table V.

Reflected Atmospheric Radiation

Anderson (1954) reported that reflected atmospheric radiation is 0.03 of atmospheric radiation for water temperatures of 0 to 30 degrees Centigrade. Daily reflected atmospheric radiation, Q_{ar}, was calculated as 0.03 Q_a and is given in Table V.

Water Surface Back Radiation

The pond surface emits radiation according to the water surface temperature. Daily water surface temperatures were calculated for the treated and untreated ponds from temperatures recorded on strip charts. Daily back radiation was calculated from a form of the Stefan-Boltzman equation

$$Q_{bs} = 0.97\ \sigma\ 86400\ T^4 \tag{90}$$

where

Q_{bs} = daily back radiation, cal/cm^2
0.97 = emissivity of water
σ = 8.132×10^{-11}, cal/cm^2-min-°K^4
86400.0 = seconds per day
T = average daily water surface temperature, °K.

Daily water surface back radiation, Q_{bs}, is given in Tables VI and VII for the treated and untreated ponds, respectively.

Stored Energy

Water stage and water temperatures at the surface, 0.5-, 1.0-, 2.0-, 4.0- and 6.0-foot depths for the beginning of each test day are

TABLE VI

DAILY BACK RADIATION FROM POND SURFACE, CHANGE IN STORED ENERGY AND HEAT OF VAPORIZATION FOR TREATED POND, 1965

Date	Back Radiation Q_{bs} cal/cm^2	Change in Stored Energy Q_o cal/cm^2	Heat of Vaporization L cal/gr
8/14	916.4	23.9	582.4
8/15	923.2	70.6	582.1
8/16	926.7	26.4	582.0
8/17	941.2	119.9	581.3
8/18	953.0	98.7	580.8
8/21	966.7	107.0	580.2
8/24	979.2	-6.9	579.6
8/25	975.2	7.4	579.8
8/26	965.8	-127.4	580.2
8/27	962.1	-43.6	580.4
8/28	961.7	23.4	580.4
8/29	960.1	-8.4	580.5
8/30	952.1	-99.6	580.8
9/1	911.6	-26.9	582.7
9/2	910.2	-65.9	582.7
9/9	962.4	-1.3	580.4
9/10	954.3	-130.8	580.7
9/14	940.3	-10.8	581.4
9/15	938.5	-31.1	581.4
9/16	925.3	-127.8	582.0
9/24	838.5	-233.0	586.1
9/25	828.8	-85.5	586.6
9/26	835.2	114.0	586.3
9/27	840.2	107.9	586.0
9/28	850.7	52.8	585.5
9/29	859.0	107.4	585.1
10/1	829.7	88.2	586.6
10/2	835.9	45.3	586.3
10/3	835.4	-48.5	586.3
10/4	834.4	-11.8	586.3
10/5	835.8	10.5	586.3

TABLE VII

DAILY BACK RADIATION FROM POND SURFACE, CHANGE IN STORED ENERGY, ADVECTED ENERGY, BOWEN"S RATIO, AND HEAT OF VAPORIZATION FOR UNTREATED POND, 1965

Date	Back Radiation Q_{bs} cal/cm^2	Change in Stored Energy Q_o cal/cm^2	Advected Energy Q_v cal/cm^2	Bowen's Ratio R -	Heat of Vaporization L cal/gr
8/14	904.0	-47.8	0.7	-0.0564	583.0
8/15	904.2	26.6	0.7	0.0457	583.0
8/16	901.9	-43.2	0.7	0.0706	583.1
8/17	907.7	73.9	0.7	-0.1034	582.8
8/18	908.5	16.5	0.7	-0.1707	582.8
8/21	931.1	107.7	0.7	0.0340	581.8
8/24	943.8	-27.4	0.7	0.0852	581.2
8/25	936.6	-18.9	0.7	-0.0472	581.5
8/26	930.5	-115.6	0.7	-0.1625	581.8
8/27	925.0	-69.8	0.7	-0.1256	582.0
8/28	923.0	25.2	0.7	0.1322	582.1
8/29	919.7	-0.5	0.7	0.0461	582.3
8/30	917.0	-84.1	0.7	-0.1092	582.4
9/1	883.6	53.3	0.6	0.1883	584.0
9/2	880.6	-57.7	0.5	0.1141	584.1
9/5	909.4	126.3	0.6	-0.0807	582.8
9/9	924.4	-60.1	0.7	-0.0230	582.1
9/10	915.0	-165.9	0.7	0.0680	582.5
9/14	901.4	-12.0	0.6	-0.2812	583.1
9/15	899.5	-58.0	0.6	-0.1819	583.2
9/16	889.5	-81.8	0.6	-0.3262	583.7
9/23	854.8	-279.6	0.5	0.2397	585.3
9/24	820.5	-260.1	0.5	0.3351	587.0
9/25	809.5	-129.5	0.4	0.2433	587.6
9/26	817.4	179.0	0.4	-0.0481	587.2
9/27	824.3	141.8	0.5	-0.0818	586.8
9/28	833.6	40.1	0.5	-0.0511	586.4
9/29	843.2	121.9	0.5	-0.1055	585.9
10/1	804.8	84.8	0.4	0.2543	587.8
10/2	810.7	22.4	0.5	0.1891	587.5
10/3	812.5	-11.1	0.5	0.2368	587.4
10/4	813.4	10.4	0.5	0.1528	587.4
10/5	815.8	31.2	0.5	0.2257	587.2
10/6	811.7	-30.8	0.5	0.2875	587.4
10/7	814.3	68.3	0.5	-0.0965	587.3
10/8	823.5	65.5	0.5	0.0038	586.9
10/9	830.5	87.4	0.5	-0.1296	586.5
10/10	837.8	47.0	0.5	-0.1220	586.2
10/13	809.9	117.4	0.5	-0.1482	587.5
10/14	821.6	121.7	0.5	-0.8030	587.0
10/15	833.4	68.7	0.5	-0.3141	586.4
10/20	820.9	-190.5	0.5	0.2525	587.0
10/21	795.5	-319.3	0.4	0.2864	588.3
10/22	770.2	-124.1	0.4	0.2064	589.6
10/23	773.8	61.2	0.4	-0.0683	589.4

given in Tables VIII and IX for the treated and untreated ponds, respectively. The volume of water for each depth increment was calculated by Equations 74 and 75. Internal energy was calculated for each depth increment by multiplying the volume of water by the average of the top and bottom temperatures. Specific heat and density were taken as unity. Total internal energy was the sum of the depth increment energies.

Surface area was calculated by Equations 76 and 77. Stored energy per unit surface area was found by dividing total internal energy by the surface area.

Change in stored energy was found by subtracting stored energy at the end of a test day from that at the beginning. Daily change in stored energy, Q_0, is given in Tables VI and VII for the treated and untreated ponds, respectively.

Advected Energy

Advected energy is the net energy gained from precipitation, inflow entering the pond and outflow leaving the pond. In this study, the only pertinent advected energy was the energy carried by the water lost as seepage from the untreated pond.

Daily advected energy lost as seepage was calculated by the equation

$$Q_v = d \rho c_p (T - T_b) \qquad (91)$$

where

Q_v = advected energy, cal/cm^2-day

d = seepage loss, cm/day

TABLE VIII

WATER STAGE AND WATER TEMPERATURE PROFILE OF TREATED POND AT 8:00 P.M., 1965

Date	Water Stage in.	Water Temperature - ^{o}F Depth from Surface - ft.					
		0.0	0.5	1.0	2.0	4.0	6.0
8/13	74.37	82.0	82.0	82.0	82.0	82.0	81.3
8/14	74.15	82.7	82.7	82.7	82.7	82.3	80.7
8/15	74.04	83.7	83.7	83.7	83.7	83.7	81.7
8/16	73.90	84.3	84.5	84.7	84.3	83.7	81.7
8/17	73.75	86.5	86.5	86.5	86.5	85.3	83.3
8/18	73.58	88.3	88.3	88.3	88.3	86.7	84.0
8/20	74.31	86.7	86.7	87.0	86.7	86.3	84.3
8/21	74.20	90.0	90.0	90.0	88.0	87.0	84.7
8/23	75.03	90.5	91.0	90.5	88.5	87.5	85.5
8/24	74.87	89.0	89.0	89.0	89.0	88.7	86.0
8/25	74.62	89.3	89.5	89.5	89.3	88.5	86.3
8/26	74.28	87.3	87.5	87.5	87.3	87.0	85.0
8/27	73.99	86.7	86.7	86.7	86.7	86.7	84.7
8/28	73.85	87.0	87.3	87.3	87.3	86.7	85.3
8/29	73.66	87.0	87.3	87.0	87.0	87.0	85.3
8/30	73.32	85.7	85.7	85.7	85.7	85.3	84.7
8/31	75.17	80.3	80.5	80.5	80.5	80.5	81.0
9/1	74.96	81.0	81.0	81.0	80.7	79.3	79.0
9/2	74.75	79.3	79.3	79.3	79.3	79.3	79.3
9/8	74.04	87.5	87.7	87.7	87.7	86.0	82.7
9/9	73.84	87.5	87.5	87.5	87.3	86.5	83.5
9/10	73.62	85.0	85.0	85.0	85.0	85.0	83.5
9/13	73.03	84.5	84.7	84.7	84.7	84.5	82.0
9/14	72.79	84.7	84.7	84.7	84.5	84.3	82.3
9/15	72.56	83.7	84.0	84.3	84.3	84.0	82.0
9/16	72.20	82.0	82.0	82.0	82.3	82.3	81.3
9/23	74.35	71.7	71.7	71.7	71.7	71.7	73.0
9/24	74.15	68.3	68.3	68.3	68.3	68.3	69.0
9/25	74.05	67.0	67.0	67.0	67.0	67.0	68.0
9/26	73.97	70.3	70.0	70.5	68.3	68.0	68.0
9/27	73.85	70.7	71.0	71.3	71.0	70.0	69.0
9/28	73.75	72.0	72.0	72.0	72.0	70.5	70.0
9/29	73.65	73.0	73.0	73.3	73.3	73.3	71.3
9/30	73.37	66.7	67.0	67.0	67.0	66.5	68.0
10/1	73.29	68.7	68.7	68.7	68.7	67.7	67.7
10/2	73.22	69.3	69.3	69.3	69.3	68.7	68.3
10/3	73.18	68.3	68.3	68.3	68.3	68.3	68.3
10/4	73.13	68.3	68.3	68.3	68.3	67.7	68.3
10/5	73.04	68.3	68.3	68.3	68.3	68.3	68.5

TABLE IX

WATER STAGE AND WATER TEMPERATURE PROFILE OF UNTREATED POND AT 8:00 P.M., 1965

Date	Water Stage in.	Water Temperature - ^{o}F Depth From Surface - ft.					
		0.0	0.5	1.0	2.0	4.0	6.0
8/13	76.32	80.7	81.0	80.7	80.7	80.5	79.7
8/14	76.00	80.0	80.0	80.0	80.0	80.0	79.5
8/15	75.78	80.5	80.7	80.7	80.5	80.3	79.5
8/16	75.54	79.7	80.0	80.0	80.0	80.0	78.5
8/17	75.25	81.0	81.3	81.3	81.3	80.7	80.0
8/18	74.90	81.7	81.7	81.3	81.3	81.3	80.7
8/20	75.53	82.0	82.0	82.0	82.0	81.0	80.3
8/21	75.35	85.3	85.3	85.0	83.3	81.5	81.0
8/23	77.72	86.0	86.3	86.5	83.0	81.7	81.0
8/24	77.44	84.0	84.0	84.0	84.0	82.0	81.5
8/25	77.08	83.0	83.3	83.3	83.0	83.3	81.0
8/26	76.66	81.3	81.5	81.5	81.3	81.3	81.3
8/27	76.28	80.7	81.0	81.0	80.0	80.3	80.3
8/28	76.04	81.0	81.0	81.0	81.0	81.0	79.7
8/29	75.74	81.0	81.0	80.7	81.0	81.0	80.7
8/30	75.33	80.0	80.0	80.0	79.7	79.7	79.7
8/31	77.21	75.5	76.0	72.3	72.7	75.5	73.5
9/1	76.94	74.3	76.0	75.5	75.5	75.0	71.7
9/2	76.65	74.5	74.5	74.5	74.5	74.3	71.7
9/4	76.49	79.5	80.0	80.0	79.3	76.3	73.7
9/5	76.29	80.0	80.3	80.3	80.3	80.3	76.7
9/8	75.60	82.5	82.7	82.7	82.7	82.7	79.5
9/9	75.30	81.5	82.0	81.7	81.7	81.7	80.0
9/10	74.97	79.3	79.0	79.3	79.3	79.3	78.7
9/13	74.18	78.5	78.5	78.5	78.5	78.5	76.3
9/14	73.84	78.5	78.5	78.5	78.5	78.5	75.5
9/15	73.53	77.7	77.7	77.7	77.7	77.7	75.0
9/16	73.10	72.0	72.7	72.7	72.7	72.7	71.0
9/22	77.00	74.0	73.5	73.5	72.7	71.7	71.0
9/23	76.73	68.5	68.5	68.5	68.5	68.5	68.5
9/24	76.49	64.5	65.0	65.0	64.7	64.7	64.7
9/25	76.32	63.3	63.7	63.3	63.0	63.0	61.0
9/26	76.21	67.0	67.0	67.0	65.0	64.7	64.7
9/27	76.05	67.7	67.7	67.7	67.7	67.7	67.0
9/28	75.89	68.3	68.3	68.3	68.3	68.3	67.7
9/29	75.75	70.0	70.3	70.0	70.0	70.0	70.0
9/30	75.42	63.0	63.7	63.3	63.0	63.0	64.3
10/1	75.28	64.7	64.7	64.7	64.5	64.3	64.7
10/2	75.15	65.0	65.0	65.0	65.0	64.7	64.7
10/3	75.08	64.7	64.7	64.7	64.7	64.7	65.0
10/4	75.01	64.7	65.0	65.0	65.0	64.7	65.0
10/5	74.89	65.3	65.3	65.3	65.3	65.3	66.0
10/6	74.78	65.5	65.5	65.0	65.0	64.5	65.0
10/7	74.59	65.7	66.0	66.0	66.0	66.0	66.0
10/8	74.46	68.5	68.5	68.5	66.5	66.0	66.0
10/9	74.34	69.0	69.0	69.0	69.0	67.3	66.7
10/10	74.21	69.3	69.3	69.3	69.3	68.7	68.0
10/12	73.81	63.7	63.7	63.7	63.7	63.7	64.5
10/13	73.70	66.0	66.3	66.0	66.0	64.7	64.7
10/14	73.62	67.5	67.5	67.5	67.5	67.5	66.0
10/15	73.54	68.5	68.5	68.5	68.5	68.5	67.3
10/19	73.73	67.5	67.7	67.7	68.0	68.0	67.5
10/20	73.53	65.0	65.0	65.0	65.0	65.0	65.7
10/21	73.20	60.0	60.3	60.3	60.3	60.3	61.7
10/22	73.02	58.5	58.5	58.5	58.5	58.5	59.7
10/23	72.89	59.5	59.5	59.5	59.5	59.5	60.0

ρ = mass density of water, g/cm^3

c_p = specific heat at constant temperature, cal/g-C

T = daily seepage temperature, °C

T_b = base temperature of 0 °C.

Specific heat and density of water were assumed to be unity. Daily advected energy, Q_v, for the untreated pond is given in Table VII.

Bowen Ratio

Bowen's ratio, R, the ratio of heat loss by conduction to that by evaporation, was calculated by Equation 18 using daily water surface and daily dry bulb air temperatures. The value of c, the coefficient of proportionality, was assumed to be 0.61. Table VII gives daily R for the untreated pond.

Heat of Vaporization

Linsley and others (1958) reported that, for temperatures up to 40 degrees Centigrade, the heat of vaporization may be accurately determined by the equation

$$L = 597.3 - 0.56\ T$$

where

L = heat of vaporization, cal/g

T = water temperature, °C.

Daily heat of vaporization, L, was calculated by the above equation using daily water surface temperatures. Tables VI and VII give daily L for the treated and untreated ponds, respectively.

CHAPTER VI

ANALYSIS OF DATA AND PRESENTATION OF RESULTS

Introduction

Evaporation from the treated and the untreated ponds was measured by a water budget. Days on which precipitation fell were omitted from the analysis to eliminate precipitation as a variable.

A mass transfer equation and a heat transfer equation were developed for the untreated pond. The mass transfer equation was applied to Lake Hefner to determine the effect of reservoir size. Heat and mass transfer equations were developed for the treated pond.

Evaporation from the treated and the untreated ponds was determined by the energy budget and compared with evaporation determined from the water budget. Evaporation reduction by the monolayer was calculated by the combined method. The combined method was modified by introducing heat and mass transfer equations developed in this study.

The effect of a monolayer on net change in stored energy was evaluated. The mass transfer equation developed for the untreated pond was compared with the mass transfer equation developed in Lake Hefner investigations. Net radiation measured by miniature net radiometers was compared with net radiation determined by the energy budget for both the treated and the untreated ponds.

A linear regression analysis was made to determine how well the equations predicted the dependent variable. The student "t" test, as described by Snedecor (1956), was used to determine if the calculated values of the y-intercept and of the slope of the regression line were different from those expected in random sampling from a normally distributed population. A perfect fit would result when the value of the y-intercept was zero and the slope of the regression line was 1.0. The "t" test was also used to determine if the differences between calculated and measured values of the dependent variable were different from those expected in random sampling from a normally distributed population. Significance was declared at the 0.05 level.

Water Budget Evaporation

Water budget evaporation was determined from changes in water surface elevation of the ponds. Daily evaporation was taken as the decrease in water elevation during the twenty-four hour period. Tables X and XI give daily water budget evaporation in centimeters for the untreated and treated pond, respectively.

Mass Transfer Equations for Untreated Pond

In Chapter III, analytical expressions based on boundary layer theory were developed for heat and mass transfer from an untreated, circular reservoir. Equation 68 is the derived equation for the average evaporation rate from a reservoir.

Wind speed and vapor pressure of the air were measured 2 meters above the mean water level of the evaporation ponds. Upon substituting 200 centimeters for z_1 and 4615.0 for R_1 into Equation 68, daily evaporation from an untreated reservoir becomes

TABLE X

EVAPORATION FROM UNTREATED POND BY WATER BUDGET, MASS TRANSFER AND ENERGY BUDGET METHODS, 1965

Date	Evaporation - cm/day		
	Water Budget	Mass Transfer Equation 96	Energy Budget
8/14	0.79	0.66	0.86
8/15	0.53	0.51	0.56
8/16	0.58	0.58	0.70
8/17	0.71	0.64	0.80
8/18	0.86	0.87	1.01
8/19	0.69	0.80	-
8/21	0.43	0.48	0.53
8/24	0.69	0.67	0.75
8/25	0.89	0.87	0.91
8/26	1.04	1.03	1.18
8/27	0.94	0.88	0.83
8/28	0.61	0.72	0.56
8/29	0.74	0.86	0.74
8/30	1.02	0.95	1.07
9/1	0.66	0.64	0.49
9/2	0.71	0.79	0.70
9/5	0.48	0.53	0.55
9/9	0.74	0.70	0.83
9/10	0.81	0.81	0.67
9/14	0.84	0.88	0.81
9/15	0.79	0.90	0.90
9/16	1.07	0.95	1.15
9/23	0.66	0.71	0.52
9/24	0.58	0.52	0.43
9/25	0.41	0.36	0.28
9/26	0.25	0.21	0.22
9/27	0.38	0.31	0.34
9/28	0.38	0.35	0.52
9/29	0.33	0.33	0.37
9/30	0.84	0.89	-
10/1	0.38	0.29	0.23
10/2	0.30	0.28	0.30
10/3	0.15	0.15	0.09
10/4	0.15	0.15	0.18
10/5	0.28	0.27	0.27
10/6	0.25	0.29	0.25
10/7	0.46	0.39	0.25
10/8	0.30	0.23	0.33
10/9	0.28	0.28	0.31
10/10	0.30	0.29	0.39
10/12	0.38	0.38	-
10/13	0.25	0.27	0.38
10/14	0.18	0.16	0.34
10/15	0.18	0.19	0.33
10/16	0.15	0.16	-
10/17	0.33	0.30	-
10/19	0.28	0.28	-
10/20	0.48	0.57	0.41
10/21	0.81	0.77	0.51
10/22	0.43	0.47	0.36
10/23	0.30	0.29	0.17

TABLE XI

EVAPORATION FROM TREATED POND BY WATER BUDGET, MASS TRANSFER AND ENERGY BUDGET METHODS, 1965

Date	Evaporation - cm/day		
	Water Budget	Mass Transfer Equation 101	Energy Budget
8/14	0.56	0.41	0.68
8/15	0.28	0.28	0.42
8/16	0.36	0.39	0.48
8/17	0.38	0.48	0.55
8/18	0.43	0.66	0.63
8/19	0.53	0.59	-
8/21	0.28	0.19	0.42
8/24	0.41	0.32	0.59
8/25	0.64	0.57	0.68
8/26	0.86	0.79	0.98
8/27	0.74	0.62	0.61
8/28	0.38	0.43	0.37
8/29	0.48	0.61	0.53
8/30	0.86	0.82	0.87
9/1	0.53	0.36	0.50
9/2	0.53	0.57	0.56
9/9	0.51	0.46	0.56
9/10	0.56	0.63	0.38
9/14	0.61	0.65	0.65
9/15	0.61	0.79	0.65
9/16	0.91	0.96	0.97
9/24	0.51	0.40	0.28
9/25	0.25	0.31	0.11
9/26	0.20	0.22	0.24
9/27	0.30	0.31	0.32
9/28	0.25	0.32	0.41
9/29	0.25	0.32	0.31
9/30	0.74	0.84	-
10/1	0.20	0.21	0.14
10/2	0.18	0.20	0.20
10/3	0.10	0.09	0.09
10/4	0.13	0.11	0.16
10/5	0.23	0.20	0.24

$$E = \frac{0.2846}{T_0} D\, Sc^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} R^{-0.11} (e_0 - e_2) \qquad (93)$$

where

E = evaporation, cm/day

0.2846 = coefficient

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

T_0 = average daily water surface temperature, ^oK

Sc = average daily Schmidt number for air, dimensionless

u_2 = average daily wind speed at a height of 2 meters, cm/sec

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

R = radius of reservoir, cm

e_0 = average daily vapor pressure of saturated air at the temperature of the water surface, mb

e_2 = average daily vapor pressure of air at a height of 2 meters, mb

Dimensions for the above parameters reflect the assumption that one cubic centimeter of water weighs one gram.

Equation 93 is for a circular reservoir but the experimental ponds were rectangular with rounded corners. The numerical value of R was taken as the radius of a circle with area equal to the surface area of the pond as calculated by Equation 77. The assumption of a circular shape should not significantly effect the length of wind travel term.

Evaporation from the untreated experimental pond was calculated by Equation 93 using parameters measured at the pond site. A linear regression analysis of calculated evaporation and measured water budget evaporation gave the equation

$$E_C = -0.00181 + 0.589\ E_{WB} \tag{94}$$

where

E_C = calculated evaporation, cm/day

E_{WB} = measured water budget evaporation, cm/day

Deviation from regression was 0.0342 centimeters with a correlation coefficient of 0.98.

Equation 93 consistently underestimated evaporation from the untreated pond. Evaporation calculated by this equation was 58.6 percent of measured evaporation. As Equation 93 contains a length term, it was deemed desirable to test it on a larger reservoir. Lake Hefner, a 2500 acre lake near Oklahoma City, was used for this evaluation.

Lake Hefner was selected for a comprehensive evaporation study in 1950 and 1951 by the U. S. Bureau of Reclamation and cooperating agencies. According to Harbeck (1954), an accurate water budget can be maintained for Lake Hefner. The reservoir is fairly regular in shape and forms a horseshoe rather than a circle as specified in Equation 93. However, the lake is more nearly circular than most large reservoirs.

The Water-Loss Investigation: Lake Hefner Studies, Base Data Report (1954) gives daily water budget evaporation, daily values for mass transfer parameters and daily lake surface area. As for the experimental pond, the radius, R, was that of a circle with the same area as the reservoir. Evaporation from Lake Hefner was calculated by Equation 93 for 177 days from July 1, 1950 to August 31, 1951. Only those days for which an accurate water budget was maintained were used.

A linear regression analysis of calculated evaporation and measured water budget evaporation gave the equation

$$E_C = 0.0284 + 0.29\ E_{WB} \tag{95}$$

Deviation from regression was 0.0405 centimeters with a correlation coefficient of 0.91.

Evaporation from Lake Hefner was underestimated by Equation 93. For the 177 days, total calculated evaporation was 30.22 centimeters and total water budget evaporation was 85.51 centimeters. Calculated evaporation was 35.3 percent of measured evaporation.

Equation 93 did not successfully predict evaporation from the untreated pond and Lake Hefner. Calculated evaporation was considerably less than measured water budget evaporation for both reservoirs. If the coefficient of Equation 93 were 0.4830, the equation would accurately predict evaporation from the untreated pond. Likewise, a coefficient of 0.8050 would accurately predict total evaporation from Lake Hefner. However, evaporation would be overestimated at low evaporation rates and underestimated at high evaporation rates for Lake Hefner.

The objective of this portion of the study was to develop a mass transfer equation with a constant coefficient to accurately predict evaporation regardless of reservoir size. Equation 93 does not satisfy this objective. A constant coefficient could be obtained by changing the exponent of the length term, R, and changing the numerical value of the coefficient in Equation 93. These modifications would give the same results as letting the numerical value of the coefficient vary with reservoir size as given in the above paragraph. Based upon this analysis, no further attempt was made to develop an evaporation equation with a length of water term.

Sleight (1917), Rohwer (1931) and other researchers have reported that under natural conditions, evaporation rates are constant for stretches of water exceeding twelve feet. If this is true, an equation estimating point evaporation may be appropriate for water storage reservoirs.

Upon assuming that the rate of evaporation is independent of the length of the water surface, the length term R, in Equation 93 has a constant numerical value. The length term was combined with the coefficient giving a new coefficient, N. The evaporation equation becomes

$$E = \frac{N}{T_0} D \, Sc^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} (e_0 - e_2) \qquad (96)$$

where

N = empirical coefficient

Evaporation measured by the water budget and measured evaporation parameters for the untreated pond were entered into Equation 96 to evaluate the coefficient. By the method of least squares, the coefficient, N, was found to be 0.2116.

Evaporation from the untreated pond was calculated by Equation 96 with a coefficient of 0.2116 to determine how well the equation fit the data from which it was developed. Calculated evaporation along with measured water budget evaporation are given in Table X. A linear regression analysis of calculated evaporation and water budget evaporation gave the equation

$$E_C = -0.00331 + 1.00\ E_{WB} \tag{97}$$

Deviation from regression was 0.0578 centimeters with a correlation coefficient of 0.98. For the 51 days on which data were collected, total calculated evaporation was 26.82 centimeters and total water budget evaporation was 27.10 centimeters.

Figure 9 compares calculated evaporation with water budget evaporation from the untreated pond. Equation 96 slightly underestimated evaporation from the experimental pond. However, the difference between calculated evaporation and water budget evaporation was not statistically significant. Results from the statistical analyses are given in Table XII. Based upon these results, it was concluded that Equation 96 with N = 0.2116 accurately predicted evaporation from the untreated pond.

Evaporation from Lake Hefner was calculated by Equation 96 to determine if a point evaporation equation is applicable to reservoirs regardless of size. Wind speed and air temperature for evaluating vapor pressure of the air were given at a height of two meters up-wind from the lake. Water surface temperature to evaluate vapor pressure at the water surface was measured near the center of the lake.

Table XIII gives calculated evaporation and measured water budget evaporation from Lake Hefner for 128 days between July 1, 1950 and August 31, 1951. Only those days were included for which an accurate water budget was maintained and no precipitation fell. A linear regression analysis of calculated evaporation and water budget evaporation gave the equation

$$E_C = 0.0677 + 1.00\ E_{WB} \tag{98}$$

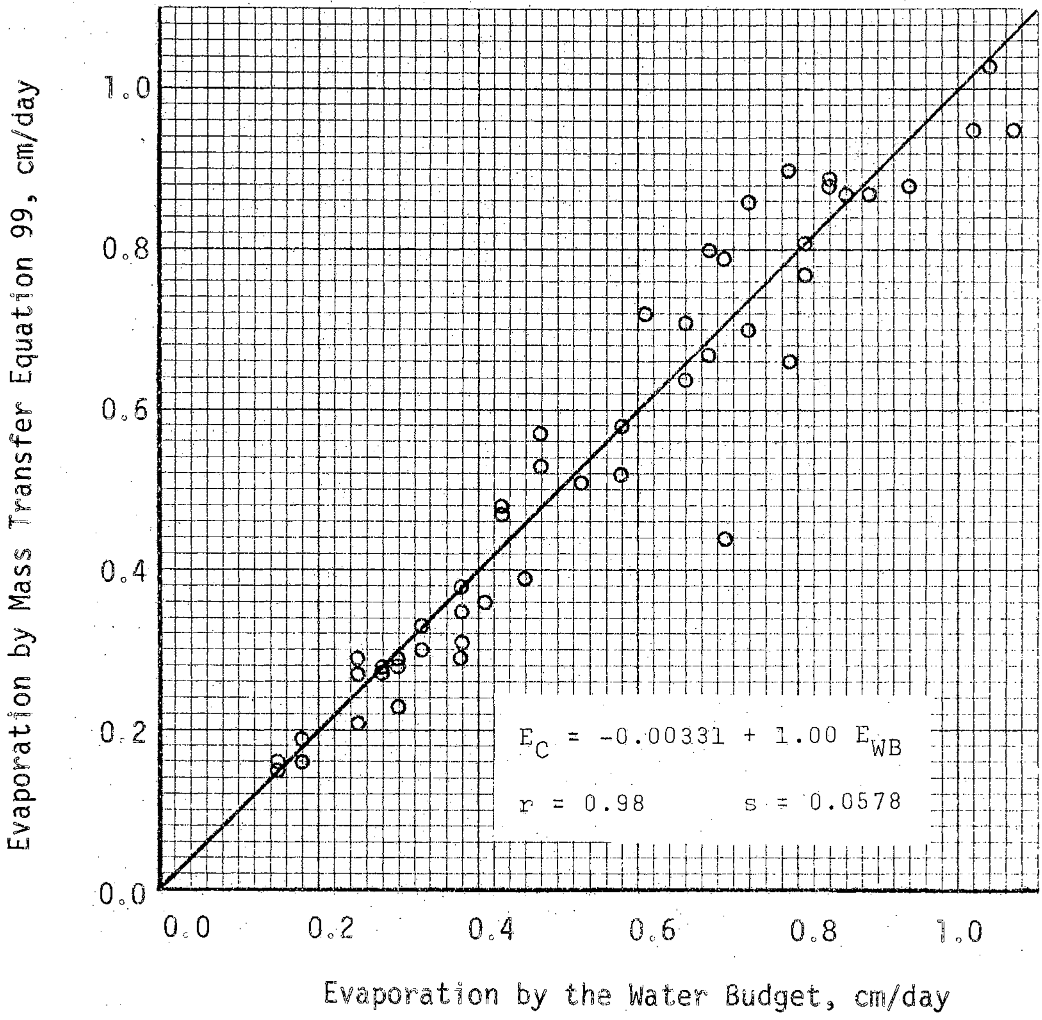


Figure 9. Comparison of Evaporation by Mass Transfer Equation 99 with Evaporation by the Water Budget for the Untreated Pond.

TABLE XII

RESULTS OF STATISTICAL ANALYSES MADE ON LINEAR REGRESSION EQUATIONS AND TEST OF DIFFERENCES

Equation Number	Statistical Parameters								
	Y-Intercept			Slope of Regression Line			Test of Differences		
	a	df	t	b	df	t	$\bar{d}$	df	t
97	-0.0033	49	-0.18	1.00	49	-0.13	0.0054	50	-0.7
98	0.0677	126	3.52	1.00	126	0.11	0.0694	127	6.9
111	0.0265	31	0.72	0.96	31	-0.52	0.0094	32	0.6
112	0.0028	43	0.07	0.99	43	-0.13	0.0018	44	-0.1
113	0.0476	29	1.12	0.97	29	-0.36	0.0337	30	1.8
116	-0.0582	29	-1.59	1.11	29	2.09	0.0123	30	0.8
118	-0.0242	29	-0.63	0.98	29	-0.29	-0.0298	30	-2.0
119	6.620	29	0.98	0.85	29	-2.09	8.1550	30	1.2

TABLE XIII

EVAPORATION FROM LAKE HEFNER BY WATER BUDGET AND MASS TRANSFER EQUATIONS, 1950-1951

Date	Evaporation - cm/day		Date	Evaporation - cm/day	
	Water Budget	Mass Transfer Equation 96		Water Budget	Mass Transfer Equation 96
7/3	0.42	0.56	10/28	0.33	0.37
7/16	0.96	1.06	10/30	0.48	0.55
8/10	0.49	0.47	11/7	0.14	0.21
8/11	0.71	0.67	11/12	0.84	0.79
8/12	0.74	1.11	11/16	0.54	0.45
8/16	0.34	0.40	11/21	0.43	0.62
8/30	1.00	0.99	11/26	0.35	0.36
8/31	1.01	1.01	11/27	0.18	0.13
9/5	0.68	0.59	11/28	0.21	0.26
9/8	0.59	0.50	11/30	0.12	0.14
9/11	0.97	0.78	12/1	0.18	0.36
9/16	0.35	0.30	12/9	0.12	0.14
9/19	0.18	0.25	12/10	0.18	0.21
9/27	0.48	0.59	12/14	0.03	0.06
9/28	0.48	0.50	12/15	0.21	0.13
9/30	0.37	0.35	12/16	0.04	0.14
10/1	0.82	0.57	12/19	0.12	0.14
10/8	0.86	0.73	12/20	0.12	0.13
10/9	0.56	0.66	12/21	0.05	0.09
10/10	0.69	0.63	12/22	0.03	0.08
10/12	0.48	0.46	12/23	0.06	0.04
10/13	0.67	0.84	12/24	0.08	0.12
10/14	0.51	0.73	12/25	0.29	0.39
10/15	0.61	0.74	1/15	0.16	0.11
10/16	0.71	0.85	1/18	0.09	0.16
10/17	0.32	0.54	1/19	0.21	0.38
10/18	0.22	0.31	1/24	0.18	0.22
10/19	0.26	0.16	2/10	0.01	0.09
10/20	0.19	0.25	3/7	0.31	0.29
10/21	0.50	0.35	3/8	0.42	0.44
10/24	0.61	0.72	3/15	0.10	0.14
10/26	1.13	1.06	3/16	0.04	0.22

TABLE XIII (Continued)

Date	Evaporation - cm/day		Date	Evaporation - cm/day	
	Water Budget	Mass Transfer Equation 96		Water Budget	Mass Transfer Equation 96
3/22	0.29	0.50	6/25	0.46	0.49
3/24	0.24	0.28	6/26	0.78	0.90
3/25	0.30	0.50	6/27	1.01	0.98
3/30	0.23	0.39	6/28	0.42	0.62
3/31	0.21	0.29	7/3	0.11	0.28
4/1	0.39	0.39	7/7	0.72	0.88
4/3	0.05	0.29	7/8	0.87	1.02
4/6	0.06	0.08	7/9	0.65	0.76
4/7	0.56	0.51	7/10	0.61	0.76
4/8	0.53	0.64	7/11	0.61	0.75
4/9	0.51	0.49	7/12	0.56	0.75
4/12	0.80	0.76	7/13	0.40	0.46
4/13	0.45	0.57	7/16	0.48	0.64
4/14	0.46	0.63	7/17	0.31	0.59
4/15	0.68	0.60	7/18	0.61	0.76
4/16	0.40	0.46	7/21	1.35	1.31
4/24	0.32	0.53	8/1	0.33	0.33
5/3	0.33	0.39	8/2	0.69	0.80
5/7	0.20	0.41	8/3	0.63	0.82
5/12	0.49	0.53	8/4	0.54	0.49
5/13	0.72	0.85	8/5	0.97	1.05
5/14	0.64	0.72	8/6	0.92	1.19
5/25	0.18	0.31	8/13	0.77	0.83
5/26	0.47	0.42	8/14	1.05	1.33
5/28	0.26	0.17	8/20	0.80	0.97
5/29	0.12	0.16	8/22	0.60	0.58
6/4	0.59	0.50	8/24	0.62	0.81
6/12	0.27	0.32	8/25	0.73	0.91
6/13	0.44	0.50	8/26	0.62	0.85
6/22	0.30	0.41	8/28	1.21	1.50
6/23	0.71	0.68	8/29	0.98	1.33
6/24	0.65	0.66	8/31	0.64	1.01

Deviation from regression was 0.114 centimeters with a correlation coefficient of 0.93. For the 128 days, calculated evaporation was 69.36 centimeters and water budget evaporation was 60.48 centimeters.

Figure 10 compares calculated evaporation with water budget evaporation for Lake Hefner. Equation 96 overestimated daily evaporation by 0.0677 centimeters. However, the comparison line between calculated evaporation and water budget evaporation had a slope of 1.0. Differences between daily calculated evaporation and water budget evaporation were significantly greater than zero when analyzed by the "t" test. Results of the statistical analyses are given in Table XII.

Equation 96 did not accurately predict evaporation from Lake Hefner. It overestimated evaporation an average of 0.0677 centimeters per day regardless of evaporation rate. These results indicated that daily evaporation from a reservoir could be predicted by

$$E = \frac{0.2116}{T_0} D\, Sc^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} (e_0 - e_2) - K_E \qquad (99)$$

where K_E is an evaporation correction factor for reservoir size. The numerical value of K_E was found to be -0.00331 centimeters per day for the untreated experimental pond and 0.0677 centimeters per day for Lake Hefner. Additional studies on reservoirs of varying sizes are needed to confirm the applicability of Equation 99 and to evaluate K_E.

Further results in this dissertation are based on the assumption that Equation 99 with K_E equal to zero accurately predicts evaporation from the untreated experimental pond.

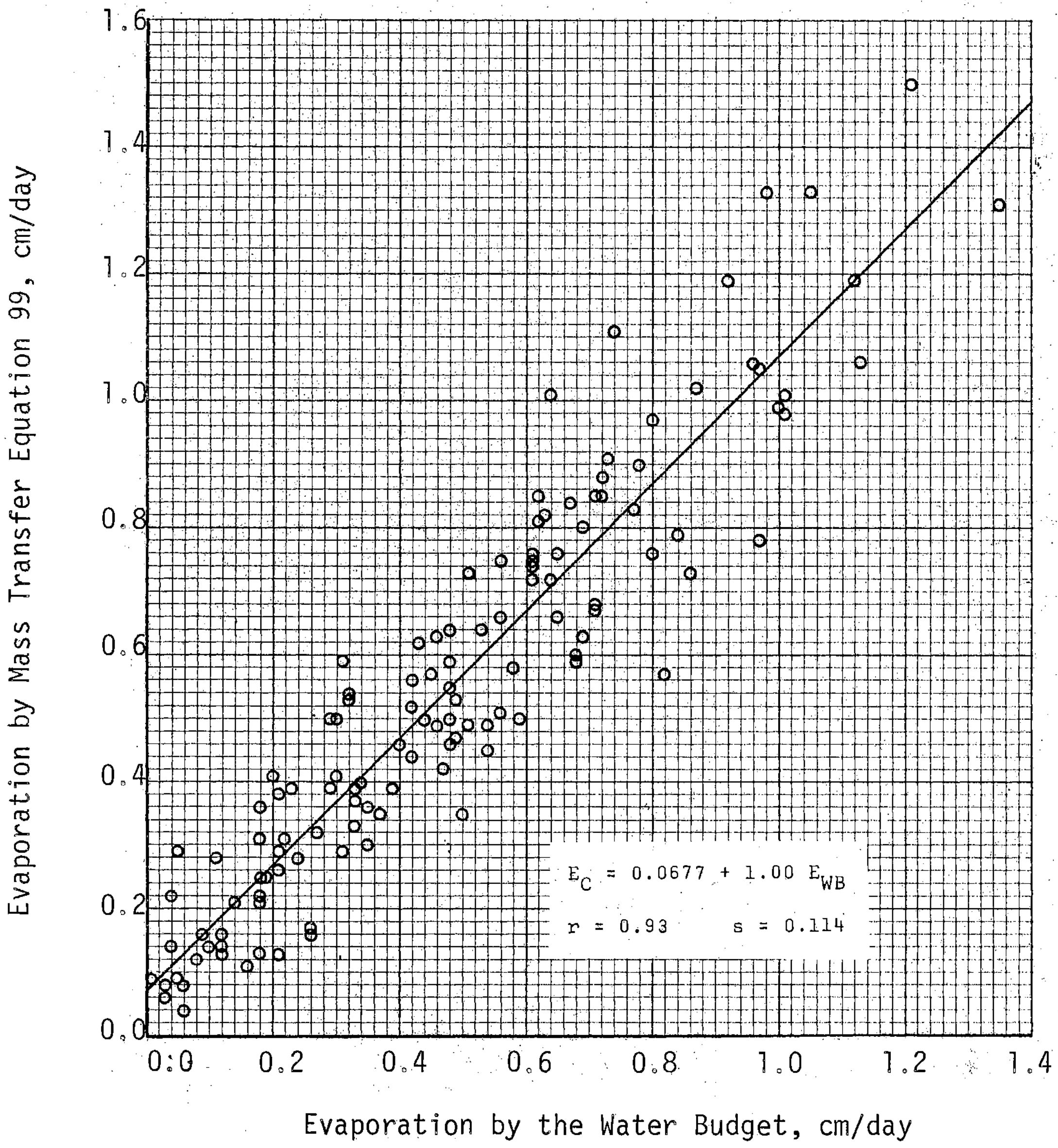


Figure 10. Comparison of Evaporation by Mass Transfer Equation 99 with Evaporation by the Water Budget for Lake Hefner, 1950-1951.

Heat Transfer Equation for Untreated Pond

Upon substituting heat transfer parameters for mass transfer parameters, the equation for heat transfer from the untreated pond becomes

$$Q_h = 976.32\ k\ Pr^{1/3}\ (\frac{u_2}{\nu})^{0.78}\ (T_0 - T_2) - K_H \qquad (100)$$

where

Q_h = heat transfer, cal/cm^2-day

976.32 = empirical coefficient

k = average daily thermal conductivity of air, cal/cm-sec-^{o}K

Pr = Prandtl number for air, dimensionless

u_2 = average daily wind speed at a height of 2 meters, cm/sec

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

T_0 = average daily water surface temperature, ^{o}K

T_2 = average daily air temperature at a height of 2 meters, ^{o}K

K_H = heat transfer correction term for reservoir size, cal/cm^2-day

Heat transfer from the untreated experimental pond can be estimated by Equation 100 with K_H equal to zero.

Heat Transfer Equation for Treated Pond

It was assumed that the presence of a monomolecular film on a water surface will not affect heat transfer from the water to the overlying air. Therefore, Equation 100 with K_H equal to zero is appropriate for estimating heat transfer from the treated experimental pond.

Mass Transfer Equation for Treated Pond

Equation 71 was derived for mass transfer from a reservoir covered with a monolayer. Evaporation from the treated experimental pond can be expressed as

$$E_T = \frac{e_0 - e_2}{R_a + R_f} \tag{101}$$

where

E_T = evaporation from treated pond, cm/day

R_a = resistance of overlying air, day-mb/cm

R_f = resistance of monolayer, day-mb/cm

From Equation 99, the resistance of the air overlying the experimental ponds is

$$R_a = \frac{T_o}{0.2116\ D\ Sc^{1/3}\ (\frac{u2}{\nu})^{0.78}} \tag{102}$$

Equation 101 was solved for resistance of the monolayer, R_f, using evaporation parameters measured at the pond site and water budget evaporation from the treated pond. These values, which will be referred to as actual film resistance, are given in Table XIV. It was then necessary to find a mathematical model to predict film resistance.

A plot of actual film resistance versus water surface temperature and wind speed indicated that film resistance is an exponential function of water temperature and wind speed. As a result, six mathematical models were selected for testing. The six models were

$$R_f = e^{(A + \frac{B}{T_o})}\ u_2^{\ C} \tag{103}$$

$$R_f = AT_o^{\ B}u_2^{\ C} \tag{104}$$

TABLE XIV

RESISTANCE OF MONOLAYER ON TREATED POND, 1965

Date	Monolayer Resistance - day - mb/cm	
	Actual	Equation 110
8/14	6.60	15.33
8/15	29.66	29.00
8/16	22.81	19.17
8/17	25.74	16.94
8/18	32.81	16.14
8/19	21.68	17.93
8/21	44.19	79.00
8/24	30.33	43.27
8/25	17.19	21.23
8/26	9.87	12.07
8/27	11.86	16.64
8/28	35.26	28.78
8/29	26.73	17.93
8/30	8.32	9.33
9/1	12.61	29.27
9/2	16.75	14.54
9/9	20.18	24.08
9/10	18.90	15.05
9/14	17.49	15.58
9/15	16.58	9.89
9/16	6.67	5.86
9/24	4.80	12.03
9/25	17.45	10.90
9/26	11.11	9.06
9/27	6.94	6.86
9/28	15.32	8.58
9/29	12.65	6.68
9/30	5.32	3.28
10/1	27.46	25.66
10/2	34.96	28.90
10/3	49.00	58.54
10/4	24.87	37.48
10/5	14.92	21.04

$$R_f = e^{(A + BT_o + Cu_2)} \qquad (105)$$

$$R_f = e^{(A + BT_o + CT_o u_2)} \qquad (106)$$

$$R_f = e^{(A + Bu_2 + CT_o u_2)} \qquad (107)$$

$$R_f = e^{(A + BT_o)} u_2^C \qquad (108)$$

where

$e = 2.718$ and A, B and C are empirical coefficients

Coefficients A, B and C were evaluated for Equations 103 through 108 by the method of least squares using measured water surface temperature and wind speed at the treated pond. Calculated values of the coefficients are given in Table XV for each mathematical model. Film resistance was then calculated by each equation using the evaluated coefficients and the measured evaporation parameters.

A linear regression analysis of film resistance calculated by the appropriate equation, Equations 103 through 108, and actual film resistance determined from Equation 101 was made for each mathematical model to determine how well the model fit the data. The regression equation was of the form

$$R_{fC} = a + b\, R_{fA} \qquad (109)$$

where

R_{fC} = calculated film resistance

R_{fA} = actual film resistance

TABLE XV

CALCULATED COEFFICIENTS FOR FILM RESISTANCE EQUATIONS FOR TREATED POND, 1965

Equation Number	Equation	Coefficient A	B	C
103	$R_f = e^{(A + \frac{B}{T_o})} u_2^C$	0.4744×10^{2}	-0.1051×10^{5}	-0.1674×10^{1}
104	$R_f = A\, T_o^B u_2^C$	0.1754×10^{9}	-0.3253×10^{1}	0.4112×10^{0}
105	$R_f = e^{(A + BT_o + Cu_2)}$	-0.1849×10^{2}	0.7526×10^{-1}	-0.3779×10^{-2}
106	$R_f = e^{(A + BT_o + CT_o u_2)}$	-0.1955×10^{2}	0.7892×10^{-1}	-0.1291×10^{-4}
107	$R_f = e^{(A + Bu_2 + CT_o u_2)}$	0.3939×10^{1}	-0.8053×10^{-1}	0.2567×10^{-3}
108	$R_f = e^{(A + BT_o)} u_2^C$	-0.1642×10^{2}	0.8651×10^{-1}	-0.1163×10^{1}

Table XVI gives values of a and b in Equation 109 for each mathematical model. Deviation from regression, s, and correlation coefficient, r, are included in Table XVI.

The "t" test was used to determine how well film resistance calculated by each mathematical model compared with actual film resistance. Values of t are given in Table XVI for each a and b. Film resistance was determined for 33 days giving 31 degrees of freedom for t. The probability of t having an absolute value greater than 2.04 for 31 degrees of freedom is 0.05.

Of the mathematical models tested, only the model described by Equation 103 adequately predicted film resistance. Upon substitution of the numberical values of the coefficients found in this analysis into Equation 103, the film resistance on the treated pond becomes

$$R_f = \frac{e^{(47.44 - \frac{10510}{T_o})}}{u_2^{1.674}} \tag{110}$$

The resistance of the film on the treated pond was calculated by Equation 110 and is given in Table XIV. Calculated film resistance is compared with actual film resistance in Figure 11.

Evaporation from the treated pond was calculated by Equation 101 to determine how well the equation predicted evaporation. Equation 110 was used to evaluate film resistance for Equation 101. Table XI gives calculated evaporation from the treated pond. A linear regression analysis of calculated evaporation and water budget evaporation gave the equation

$$E_C = 0.02645 + 0.96\ E_{WB} \tag{111}$$

TABLE XVI

COEFFICIENTS OF LINEAR REGRESSION EQUATION 108 AND CALCULATED t VALUES FOR TREATED POND, 1965

Film Resistance Equation Number	Coefficients and t values for Regression Equation 108 a	t	b	t	Correlation Coefficient r	Deviation from Regression s
103	-1.59	-0.47	1.12	0.83	0.80	9.49
104	19.34	28.84	-0.17	-39.51	-0.71	1.86
105	8.25	4.42	0.51	-5.96	0.74	5.18
106	8.10	4.21	0.52	-5.63	0.74	5.34
107	8.20	5.29	0.51	-7.11	0.80	4.30
108	1.53	2.56	0.71	-3.18	0.82	5.71

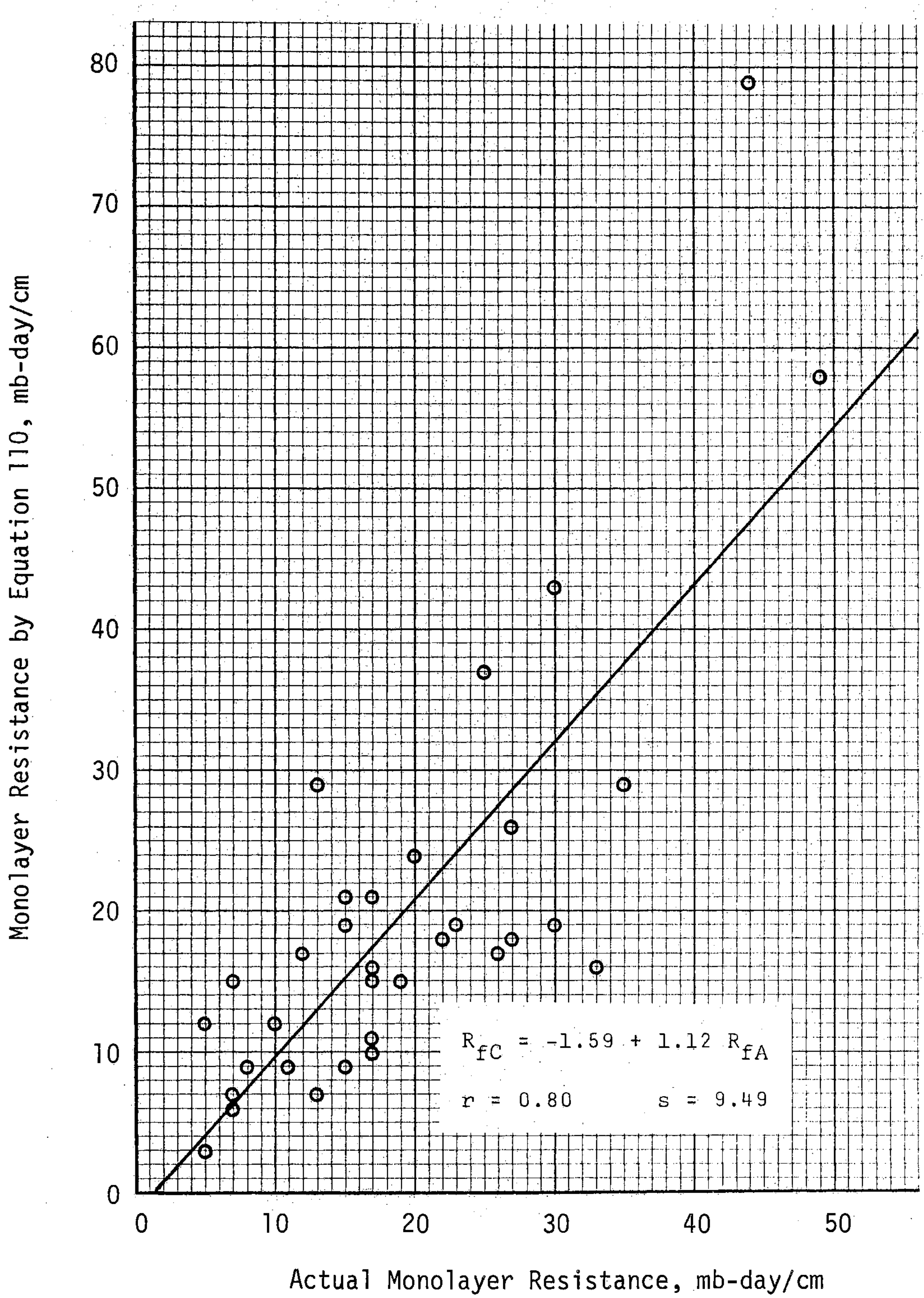


Figure 11. Comparison of Monolayer Resistance by Equation 110 with Actual Monolayer Resistance for the Treated Pond.

Deviation from regression was 0.09120 centimeters with a correlation coefficient of 0.92. For the 33 days on which data were available, total calculated evaporation was 15.12 centimeters and total water budget evaporation was 14.81 centimeters.

Calculated evaporation is compared with water budget evaporation in Figure 12. Results from the "t" tests on the y-intercept, slope of the regression line and differences between calculated and measured evaporation are given in Table XII. Equation 101 adequately predicted evaporation from the treated pond.

Evaporation from Untreated Pond by the Energy Budget

Parameters for estimating evaporation from the untreated pond by the energy budget were measured at the pond on 45 days. Evaporation was calculated by the energy budget and is given in Table X. A linear regression analysis of calculated energy budget evaporation versus water budget evaporation gave the equation

$$E_{EB} = 0.00284 + 0.99\ E_{WB} \tag{112}$$

where

E_{EB} = evaporation calculated by the energy budget, cm/day

Deviation from regression was 0.1105 centimeters with a correlation coefficient of 0.92. For the 45 days, total evaporation as calculated by the energy budget was 24.36 centimeters and total water budget evaporation was 24.43 centimeters.

Evaporation as calculated by the energy budget is compared with water budget evaporation for the untreated pond in Figure 13. Table XII gives results of the "t" tests on the y-intercept, slope of the

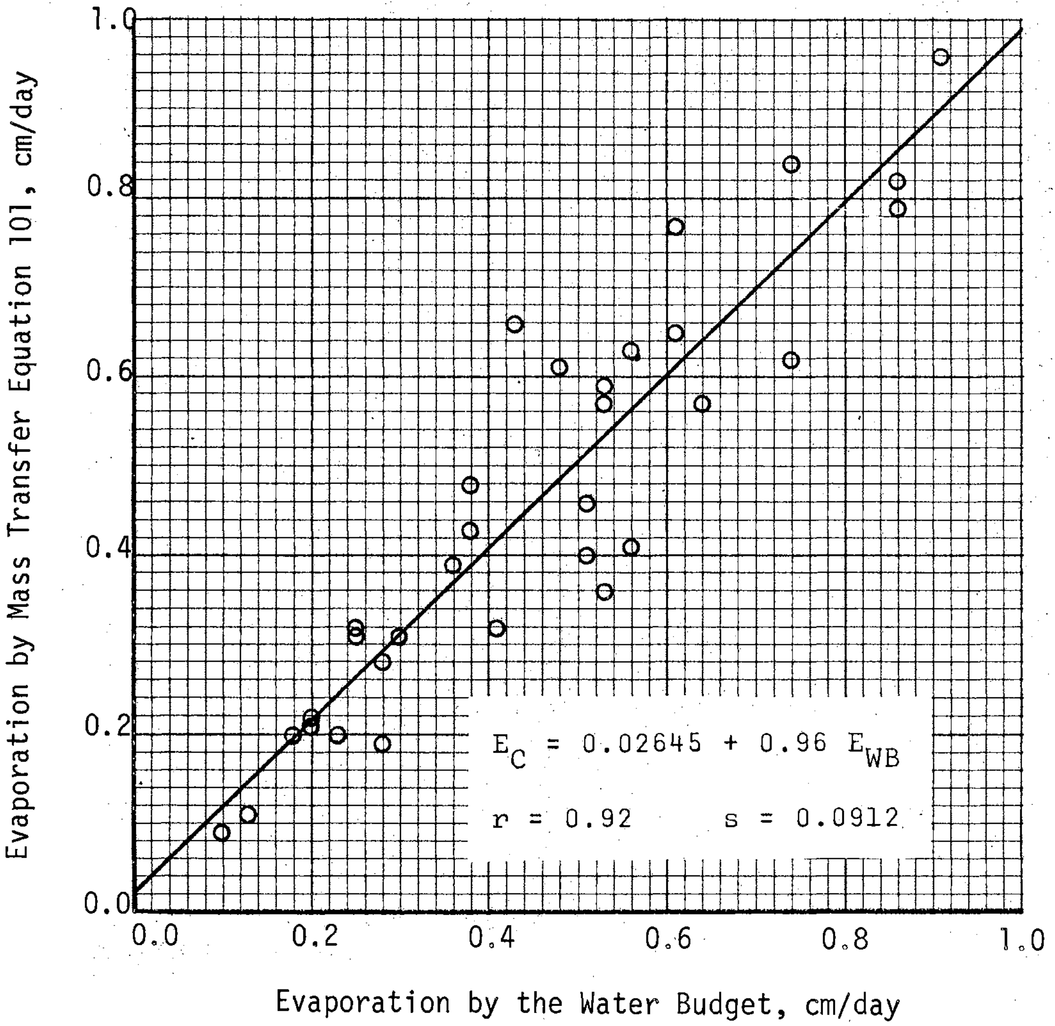


Figure 12. Comparison of Evaporation by Mass Transfer Equation 101 with Evaporation by the Water Budget for the Treated Pond.

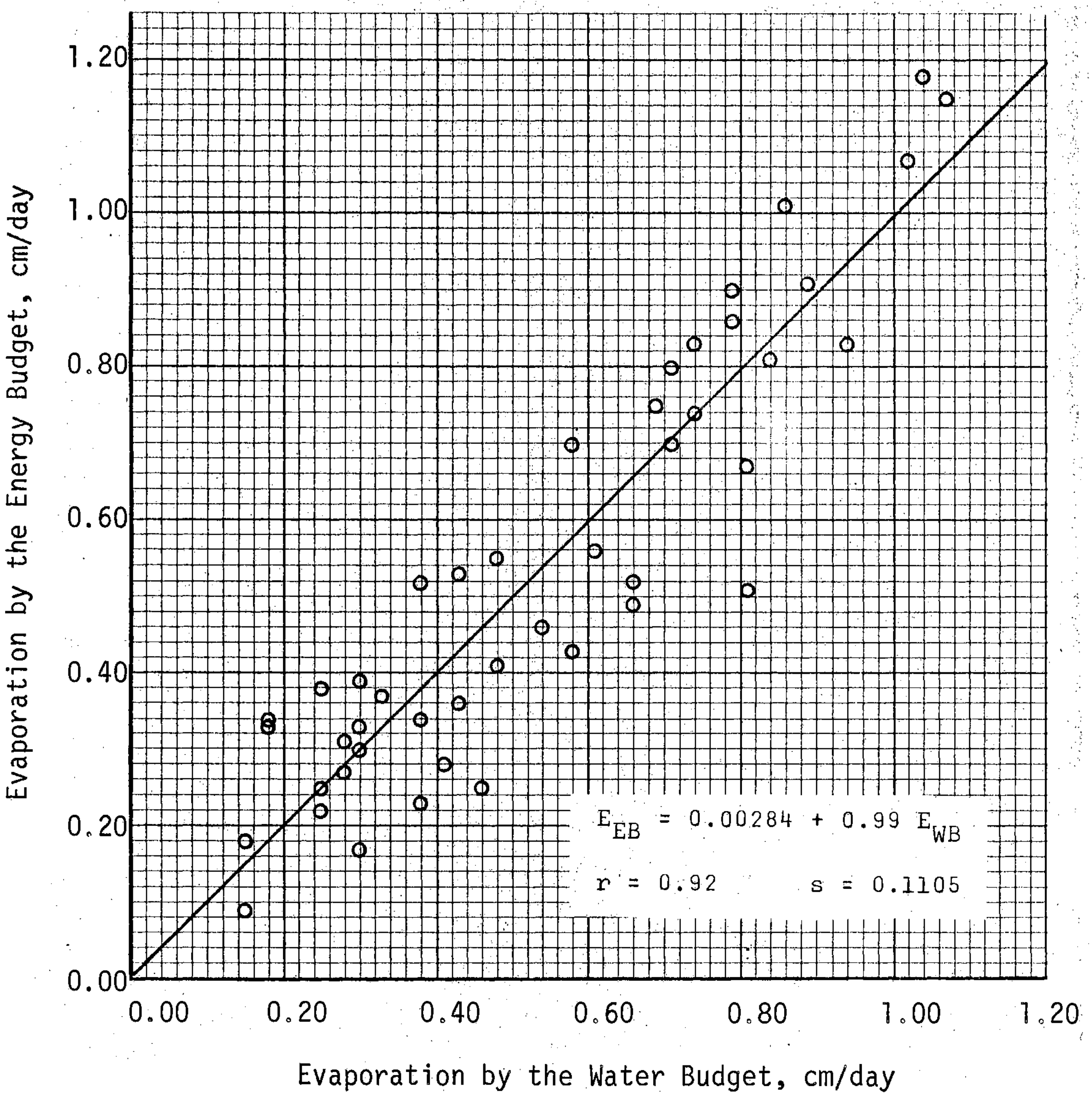


Figure 13. Comparison of Evaporation by the Energy Budget with Evaporation by the Water Budget for the Untreated Pond.

regression line and differences between evaporation calculated by the energy budget and water budget evaporation. The energy budget accurately predicted evaporation from the untreated pond.

Evaporation from Treated Pond by the Energy Budget

Parameters for estimating evaporation from the treated pond by the energy budget were measured on 31 days. Evaporation was calculated by the energy budget and is given in Table XI. A linear regression analysis of calculated energy budget evaporation versus water budget evaporation gave the equation

$$E_{EB} = 0.04757 + 0.97\ E_{WB} \qquad (113)$$

Deviation from regression was 0.1053 centimeters with a correlation coefficient of 0.97. For the 31 days, total evaporation as calculated by the energy budget was 14.58 centimeters and total water budget evaporation was 13.54 centimeters.

Figure 14 compares calculated evaporation by the energy budget with water budget evaporation. The "t" test was used to determine how well calculated evaporation matched water budget evaporation. Results from the "t" tests are given in Table XII. The y-intercept of the regression line was not significantly different from zero, the slope of the regression line was not significantly different from 1.0 and differences between calculated and measured evaporation were not significantly different from zero.

Although there was no statistically significant difference between evaporation calculated by the energy budget and evaporation measured by the water budget, the energy budget consistently overestimated evapora-

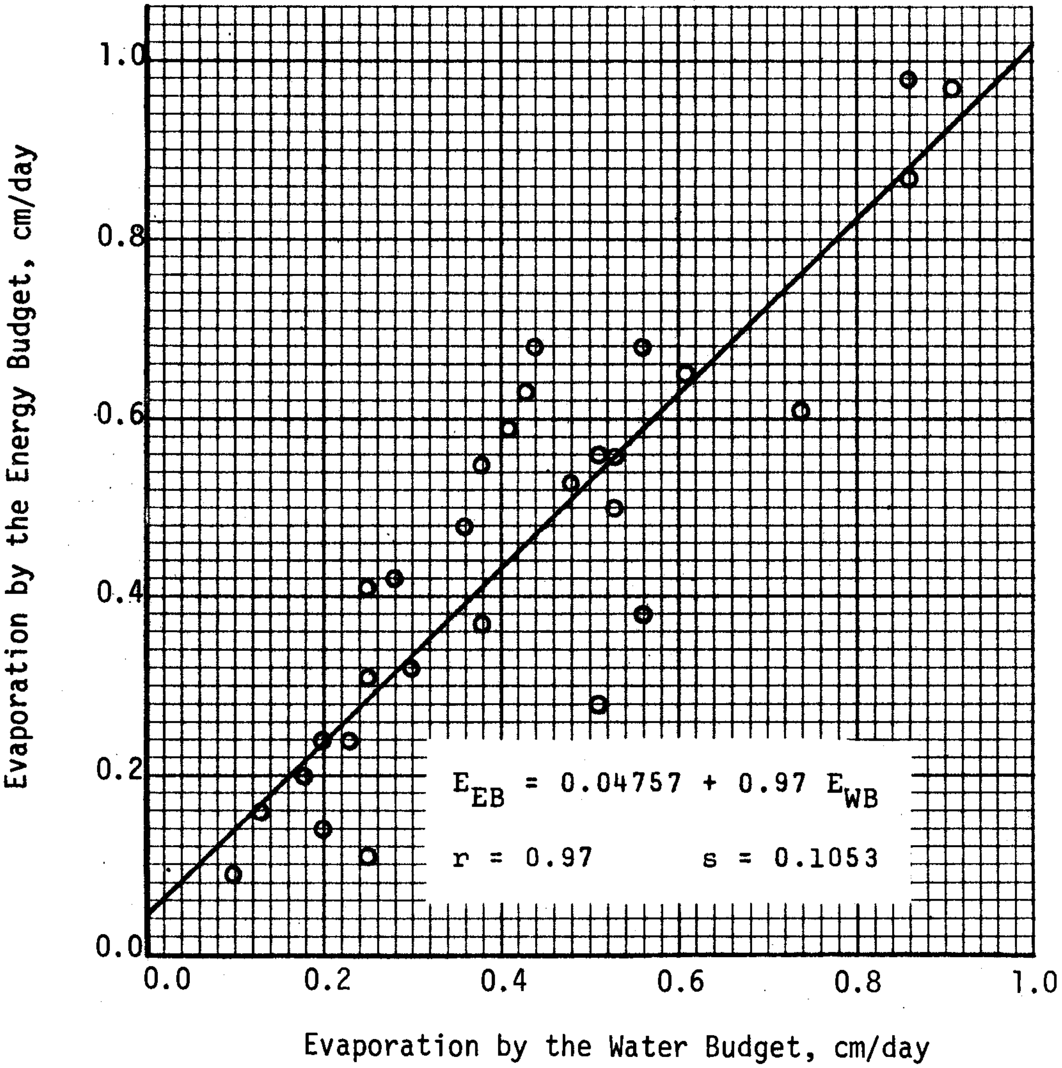


Figure 14. Comparison of Evaporation by the Energy Budget with Evaporation by the Water Budget for the Treated Pond.

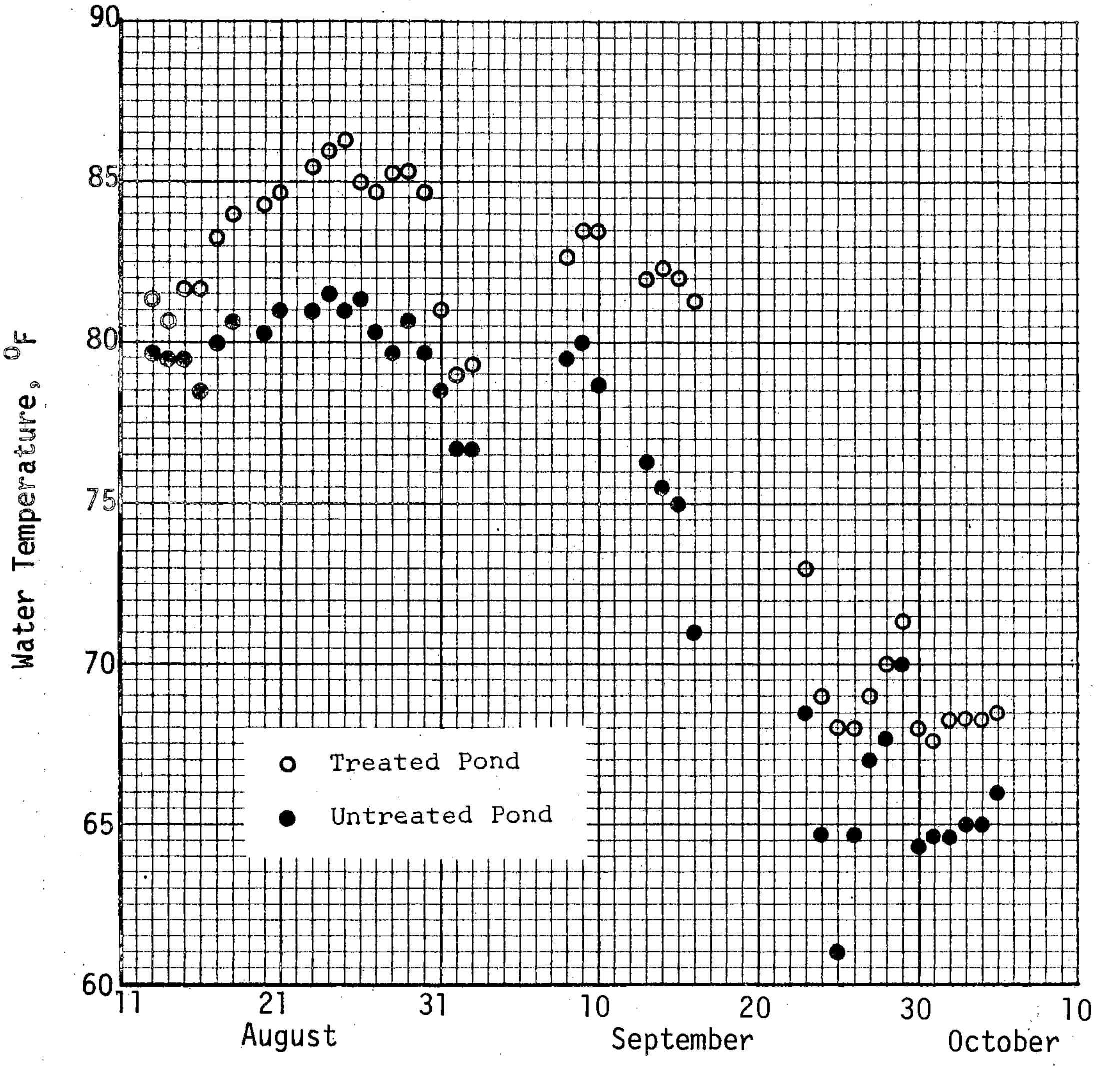
tion. This can be attributed to the assumption in the energy budget that heat transfer through the bottom of the pond can be neglected. The temperature of the soil profile underlying the ponds was in equilibrium with the overlying water at the beginning of the study. After a monolayer was applied to the treated pond, the water temperature at the bottom of the treated pond was consistently higher than in the untreated pond as shown in Figure 15. The increased temperature gradient into the soil underlying the treated pond led to energy loss as heat. The energy budget assumed that this energy loss was available for evaporation and therefore overestimated evaporation. When the temperature of the soil profile beneath the treated pond comes into equilibrium with the temperature of the water in the treated pond, energy losses through the bottom of the pond should become small and can be neglected. After a monolayer is maintained on the pond for sufficient time for the soil temperature to come to equilibrium with the water temperature, the energy budget may accurately predict evaporation from the treated pond.

Evaporation Reduction by the Combined Method

Harbeck and Koberg developed a method for evaluating evaporation reduction by a monolayer using a combination of energy budget and heat and mass transfer equations. The method, called the combined method, is described in Chapter II.

For the experimental ponds, the energy consumed in evaporating water and that conducted as sensible heat can be expressed as

$$Q_h = K\, u_2\, (T_o - T_2) \qquad (114)$$



Date, 1965

Figure 15. Water Temperature 6-Feet Below the Surface Measured at 8:00 P.M. for the Treated and Untreated Ponds.

and

$$Q_e = \rho L N u_2 (e_0 - e_2) \tag{115}$$

where

Q_h = energy conducted from water to overlying air, cal/cm^2-day
K = empirical coefficient
u_2 = wind speed at a height of 2 meters, cm/sec
T_0 = water surface temperature, ^oK
T_2 = temperature of the air at a height of 2 meters, ^oK
Q_e = energy of evaporation, cal/cm^2-day
ρ = density of water taken as unity, gr/cm^3
L = heat of vaporization, cal/gr
N = empirical coefficient
e_0 = vapor pressure of saturated air at the water surface temperature, mb
e_2 = vapor pressure of the air at a height of 2 meters, mb

Daily values of K and N were calculated for the untreated pond for Equation 114 and 115 using values of Q_e and Q_h determined by the energy budget and values of the evaporation parameters measured at the pond site. The coefficients K and N were taken as the average of the daily values and were found to be 0.07197 and 0.0002508, respectively.

Evaporation assuming no monolayer had been applied was calculated for the treated pond by the combined method and is given in Table XVII. Water budget evaporation from the untreated pond, which is the evaporation without a monolayer, is also given in Table XVII. A linear regression analysis comparing calculated evaporation with water budget evaporation gave the equation

TABLE XVII

WATER BUDGET EVAPORATION FROM UNTREATED POND AND ESTIMATED EVAPORATION FROM TREATED POND ASSUMING NO MONOLAYER HAD BEEN APPLIED, 1965

Date	Water Budget cm/day	Estimated Evaporation Combined Method cm/day	Estimated Evaporation Modified Combined Method cm/day
8/14	0.79	0.73	0.52
8/15	0.53	0.50	0.43
8/16	0.58	0.61	0.53
8/17	0.71	0.72	0.64
8/18	0.86	0.91	0.87
8/21	0.43	0.51	0.42
8/24	0.69	0.72	0.57
8/25	0.89	0.91	0.80
8/26	1.04	1.22	0.96
8/27	0.94	0.87	0.82
8/28	0.61	0.62	0.67
8/29	0.74	0.81	0.82
8/30	1.02	1.13	0.95
9/1	0.66	0.61	0.55
9/2	0.71	0.76	0.73
9/9	0.74	0.75	0.67
9/10	0.81	0.70	0.81
9/14	0.84	0.90	0.84
9/15	0.79	0.95	0.93
9/16	1.07	0.23	1.03
9/24	0.58	0.43	0.48
9/25	0.41	0.27	0.36
9/26	0.25	0.28	0.25
9/27	0.38	0.38	0.34
9/28	0.38	0.45	0.37
9/29	0.33	0.39	0.36
10/1	0.38	0.24	0.29
10/2	0.30	0.26	0.28
10/3	0.15	0.14	0.16
10/4	0.15	0.17	0.16
10/5	0.28	0.28	0.27

$$E_C = -0.05182 + 1.11\ E_{WB} \tag{116}$$

Deviation from regression was 0.07855 centimeters with a correlation coefficient of 0.97. Total calculated evaporation was 19.43 centimeters and total water budget evaporation was 19.05 centimeters for 31 days.

Figure 16 compares calculated evaporation with water budget evaporation. Calculated values of t to determine how well the combined method predicted evaporation assuming no monolayer had been applied are given in Table XII. The y-intercept of the regression line was not significantly different from zero but the slope of the regression line was significantly different from 1.0. The difference between calculated evaporation from the treated pond assuming no monolayer and water budget evaporation for the untreated pond were not significantly different from zero. Therefore, the combined method significantly underestimated evaporation on days when evaporation was low and overestimated evaporation on days when evaporation was high. However, considering the total 31 days, there was no significant difference between evaporation estimated by the combined method for the treated pond and measured water budget evaporation for the untreated pond.

Although not statistically significant, evaporation reduction by the monolayer was underestimated by the combined method. By the energy budget, evaporation from the treated pond for 31 days totaled 14.58 centimeters. Total evaporation, calculated by the combined method, was 19.43 centimeters. Calculated evaporation reduction by the monolayer was 4.85 centimeters or 24.96 percent. Measured water budget evaporation from the treated and untreated ponds was 13.54 centimeters

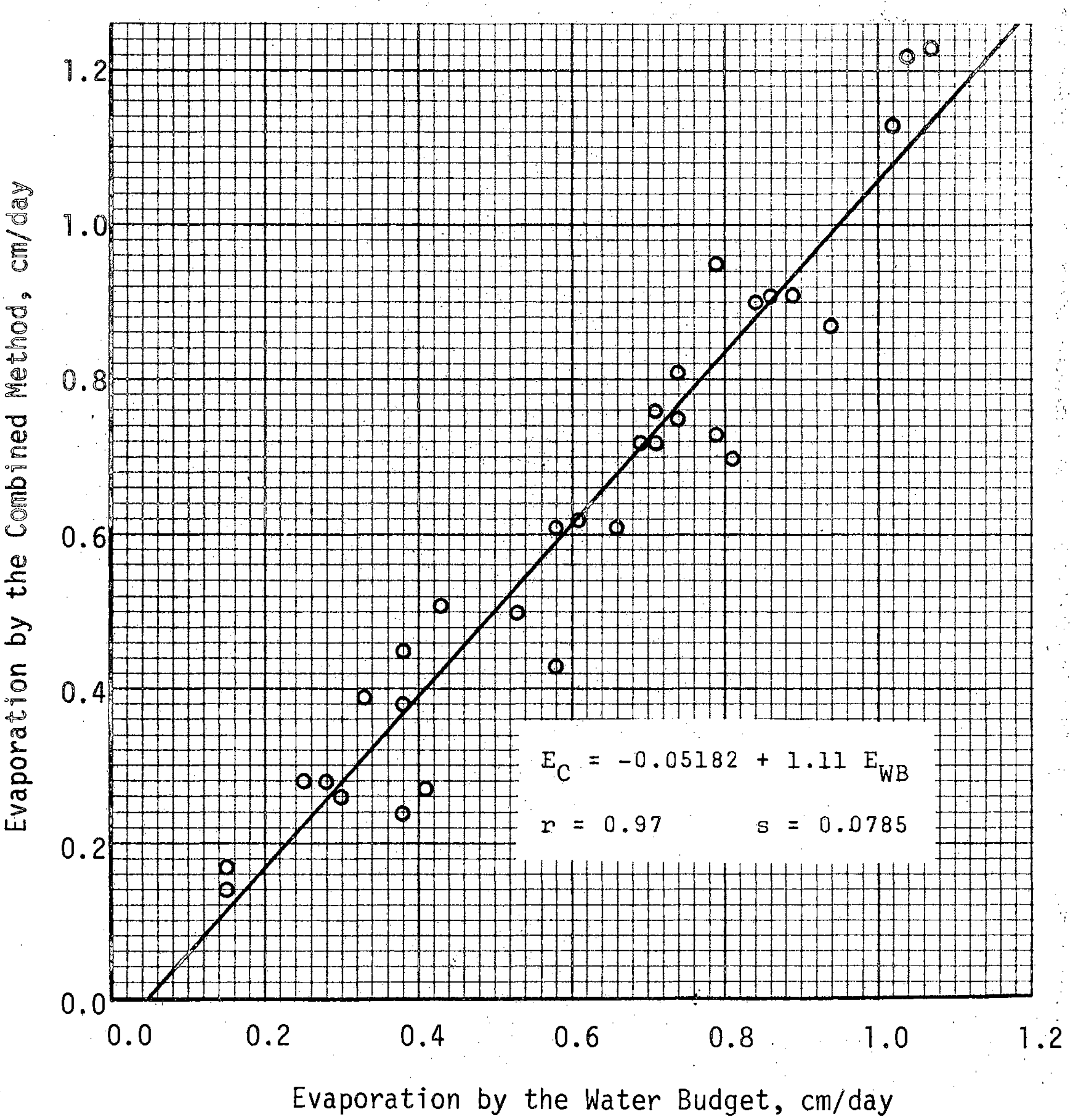


Figure 16. Comparison of Estimated Evaporation from the Treated Pond by the Combined Method with Evaporation From the Untreated Pond by the Water Budget.

and 19.05 centimeters, respecitvely, for 31 days. Measured evaporation reduction by the monolayer was 5.51 centimeters or 28.92 percent.

Total evaporation assuming no monolayer had been applied, calculated by the combined method for the treated pond, was 0.38 centimeters greater than measured from the untreated pond. However, the energy budget overestimated evaporation from the treated pond by 1.04 centimeters. Therefore, the combined method underestimated evaporation reduction by the monolayer by 0.66 centimeters.

Evaporation Reduction by the Modified Combined Method

The combined method for estimating evaporation reduction was modified using heat and mass transfer equations developed in this study. Evaporation from the treated pond was calculated by Equation 101 rather than the energy budget. Equation 100 with K_H equal to zero replaced Equation 114. Equation 115 was replaced by the equation

$$Q_e = \rho L[\frac{0.2116}{T_o} D\ Sc^{1/3} (\frac{u2}{\nu})^{0.78} (e_0 - e_2) - K_E] \qquad (117)$$

with K_E equal to zero.

Evaporation from the treated pond assuming no monolayer had been applied was calculated by the modified combined method for the same 31 days included in the combined method analysis and is given in Table XVII. A linear regression analysis of calculated evaporation assuming no monolayer versus water budget evaporation for the untreated pond gave the equation

$$E_C = -0.02422 + 0.98\ E_{WB} \qquad (118)$$

Deviation from regression was 0.08331 centimeters with a correlation coefficient of 0.95. Total calculated evaporation was 17.98 centimeters and total water budget evaporation was 19.05 centimeters for 31 days.

Figure 17 compares calculated evaporation by the modified combined method for the treated pond with water budget evaporation from the untreated pond. Results of the "t" test to determine how well calculated evaporation matched measured evaporation are given in Table XII. There was no significant difference between calculated and measured evaporation.

The modified combined method underestimated evaporation reduction by the monolayer. Evaporation from the treated pond, calculated by Equation 101, totaled 13.69 centimeters for 31 days. Total evaporation calculated by the modified combined method was 17.98 centimeters. Calculated evaporation reduction by the monolayer was 4.29 centimeters or 23.86 percent. Water budget evaporation from the treated and untreated ponds was 13.54 centimeters and 19.05 centimeters, respectively. Measured evaporation reduction by the monolayer was 5.51 centimeters or 28.92 percent. The modified combined method underestimated evaporation reduction by the monolayer by 1.22 centimeters.

Effect of a Monolayer on Change in Stored Energy

Both the combined method and the modified combined method underestimated evaporation reduction by the monolayer. These results indicate an erroneous assumption in their development.

In Equation 30, it was assumed that the presence of a monolayer will not affect the following terms; Q_s, Q_r, Q_a, Q_{ar}, Q_v and Q_o. The quantity of solar radiation, Q_s, and atmospheric radiation, Q_a,

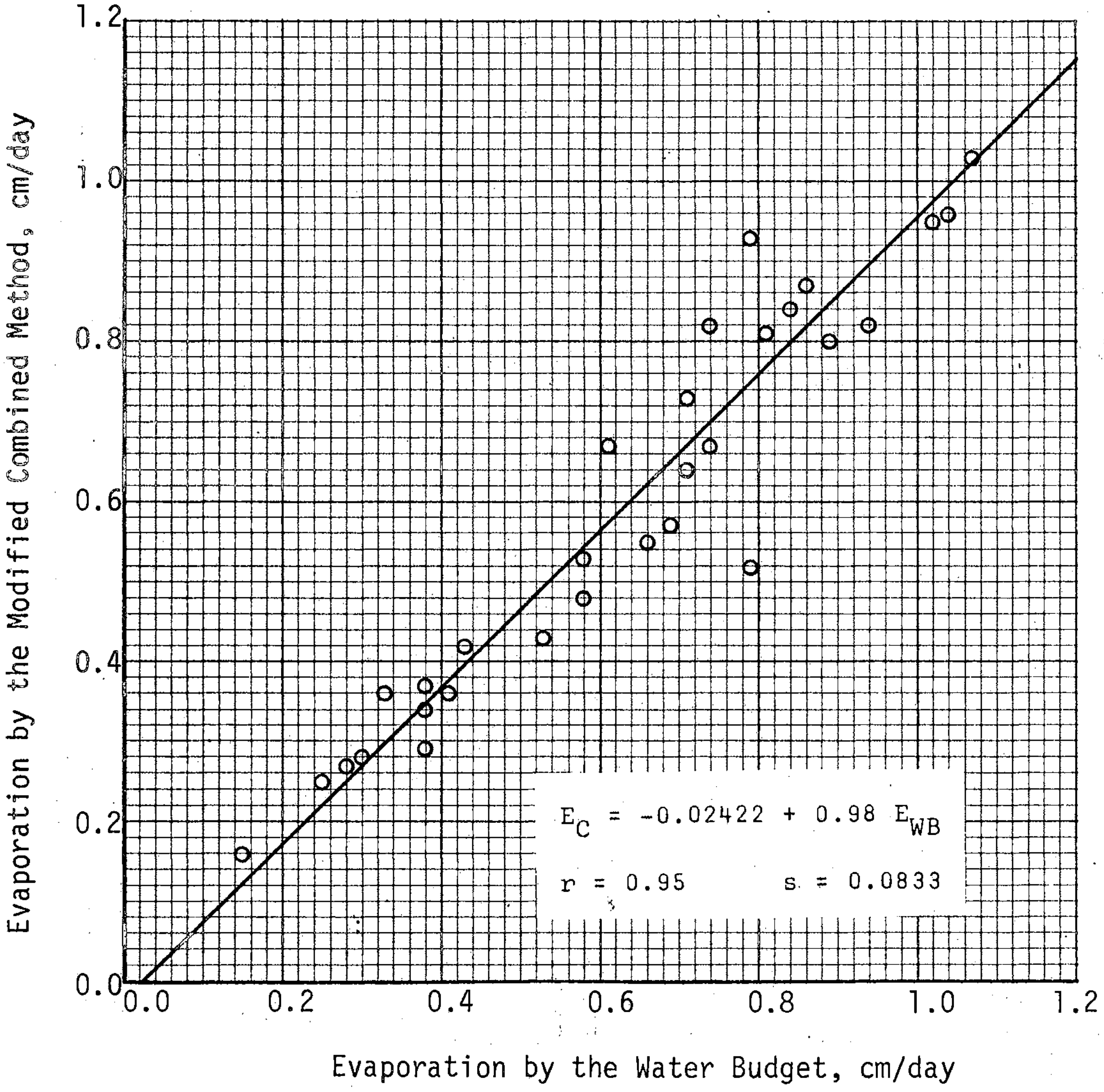


Figure 17. Comparison of Estimated Evaporation from the Treated Pond by the Modified Combined Method with Evaporation from the Untreated Pond by the Water Budget.

reaching a reservoir surface will not be influenced by the presence or absence of a monolayer. A monolayer may alter the reflective properties of the reservoir surface and therefore the magnitude of Q_r and Q_{ar}. Beard and Wiebelt (1966) found that a monolayer does not significantly change reflected energy from a flat water surface. They did report that the presence of water waves decreased the theoretical reflectance from a water surface up to 20 percent. Waves would be present on an untreated reservoir and their size would depend upon wind velocity and reservoir size. Thus, reflected energy would be increased when a monolayer is present on a reservoir. As the magnitude of the reflected radiation terms is small as shown in Table V, the change in reflectance due to a monolayer is small and can be neglected. There was no energy advected into or from the treated pond. Therefore, the only term assumed to be negligible in the combined method which could lead to a significant error is the net change in stored energy, Q_o. This possibility was discussed by Runkles and others (1964).

The net change in stored energy was determined for both the treated and the untreated pond for the energy budget and is given in Table XVIII. A linear regression analysis of net change in stored energy for the treated pond versus net change in stored energy for the untreated pond gave the equation

$$Q_{oT} = 6.620 + 0.85\ Q_{oUT} \tag{119}$$

where

Q_{oT} = net change in stored energy for treated pond, cal/cm^2-day

Q_{oUT}= net change in stored energy for untreated pond, cal/cm^2-day

TABLE XVIII

NET CHANGE IN STORED ENERGY FOR EVAPORATION PONDS, 1965

Date	Net Change in Stored Energy		
	Treated Pond cal/cm^2-day	Untreated Pond cal/cm^2-day	Difference cal/cm^2-day
8/14	23.9	-47.8	71.7
8/15	70.6	26.6	44.0
8/16	26.4	-43.2	69.6
8/17	119.9	73.9	46.0
8/18	98.7	16.5	82.2
8/21	107.0	107.7	-0.7
8/24	-6.9	-27.4	20.5
8/25	7.4	-18.9	26.3
8/26	-127.4	-115.6	-11.8
8/27	-43.6	-69.8	26.2
8/28	23.4	25.2	-1.8
8/29	-8.4	-0.5	-7.9
8/30	-99.6	-84.1	-15.5
9/1	-26.9	53.3	-80.2
9/2	-65.9	-57.7	-8.2
9/9	-1.3	-60.1	58.8
9/10	-130.8	-165.9	35.1
9/14	-10.8	-12.0	1.2
9/15	-31.1	-58.0	26.9
9/16	-127.8	-81.8	-46.0
9/24	-233.0	-260.1	27.1
9/25	-85.5	-129.5	44.0
9/26	114.0	179.0	-65.0
9/27	107.9	141.8	-33.9
9/28	52.8	40.1	12.7
9/29	107.4	121.9	-14.5
10/1	88.2	84.8	3.4
10/2	45.3	22.4	22.9
10/3	-48.5	-11.1	-37.4
10/4	-11.8	10.4	-22.2
10/5	10.5	31.2	-20.7

Deviation from regression was 37.23 calories with a correlation coefficient of 0.91.

Figure 18 compares net change in stored energy for the treated and untreated ponds. Results of the "t" tests to determine if net change in stored energy was the same for both ponds are given in Table XII. The Y-intercept of the regression line was not significantly different from zero but the slope of the regression line was significantly different from 1.0. The difference in net change in stored energy was not significantly different from zero.

While the overall change in net stored energy between the treated and untreated ponds was not statistically significant, the day to day change was statistically significant. Therefore, the assumption of negligible net change in stored energy with the application of a monolayer is in error. Underestimation of evaporation reduction by the monolayer by the combined method and the modified combined method was attributed to this erroneous assumption.

Comparison of Mass Transfer Equations

The mass transfer equation developed in the Lake Hefner investigations, as applied to the experimental ponds, is

$$E = Nu_2 \, (e_0 - e_2) \tag{120}$$

where

E = evaporation, cm/day

This equation is commonly used in the combined method when evaluating evaporation reduction by a monolayer. From previous evaporation investigations, the mass transfer coefficient, N, appeared to have a

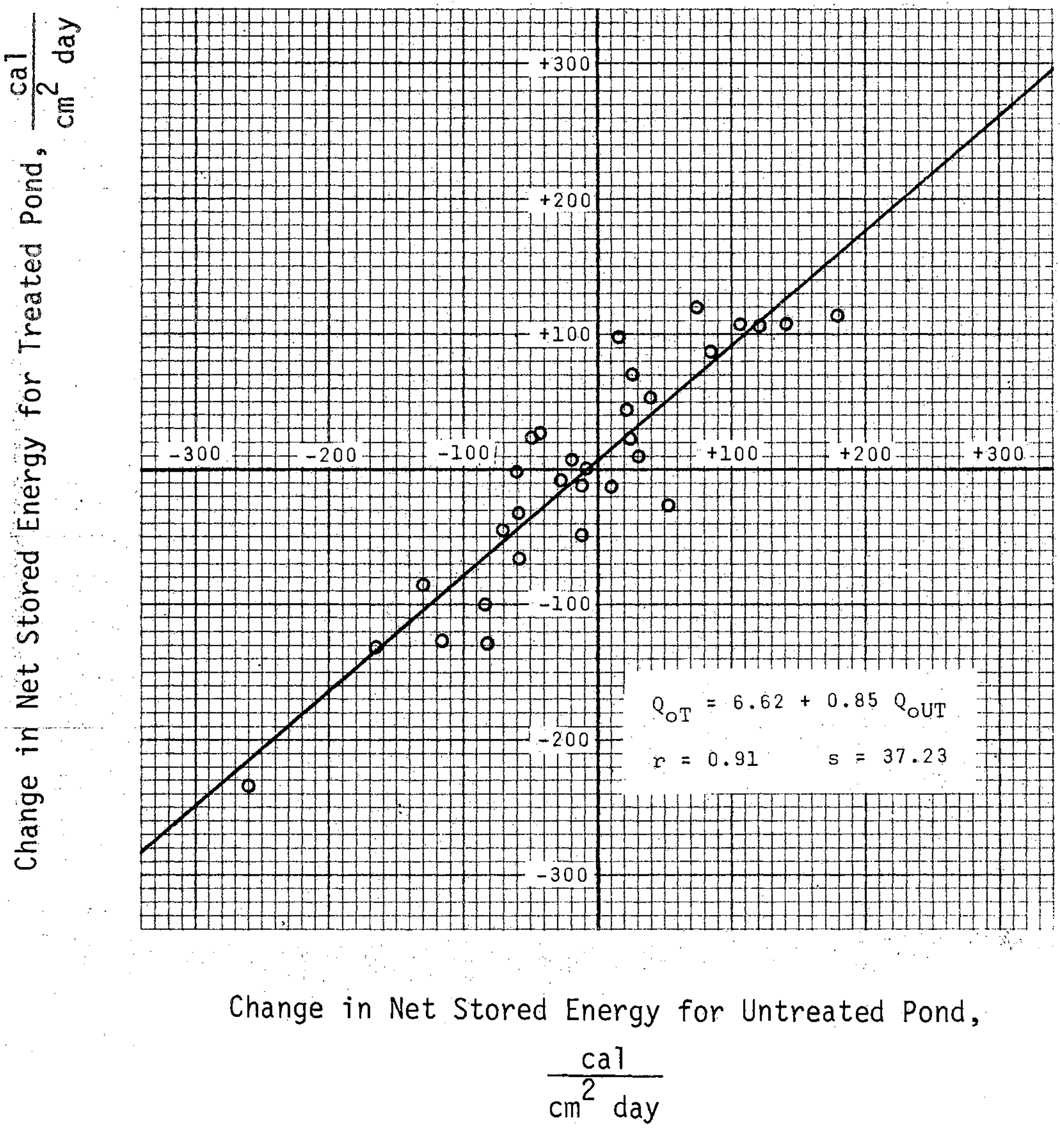


Figure 18. Comparison of Change in Net stored Energy for Treated Pond with Change in Net Stored Energy for Untreated Pond.

seasonal variation. Fry (1967) attempted to describe the seasonal variation of N by an equation but was unsuccessful. However, he was successful in predicting evaporation with a polynomial which included independent variables describing seasonal effects. These variables were water surface temperature, wind speed, air temperature and relative humidity of the air.

The mass transfer coefficient of Equation 120 was evaluated for the untreated pond. The average value of N was 0.0002058. Figure 19 shows the variation in N for the period August 14 through October 23.

Equation 99 with K_E equal to zero was developed for the untreated pond. The mass transfer coefficient was found to be 0.2116. Figure 20 shows the variation in the coefficient for the period August 14 through October 23.

Results from this study indicate that the mass transfer equation developed for the untreated pond, Equation 99, is a better predictor of evaporation than the mass transfer equation developed at Lake Hefner, Equation 120. Excellent agreement was found between predicted evaporation by Equation 99 with K_E equal to zero and water budget evaporation for the untreated pond. In addition, examination of Figures 19 and 20 shows less day to day variation in the magnitude of the mass transfer coefficient of Equation 99 than of the coefficient in Equation 120. The duration of the study was too short to establish a definite seasonal effect on the mass transfer coefficients.

Miniature Net Radiometers

The first five terms of the energy Equation 22 estimate net radiation absorbed at the reservoir surface. Their measurement requires

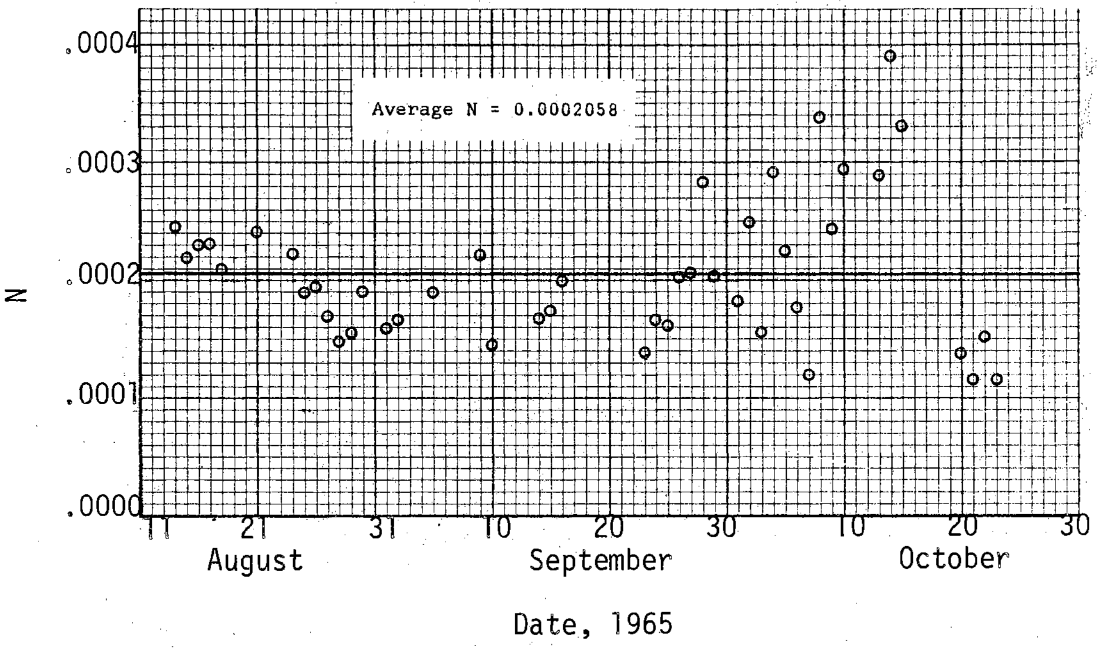


Figure 19. Daily Values of N for Mass Transfer Equation 120 for the Untreated Pond.

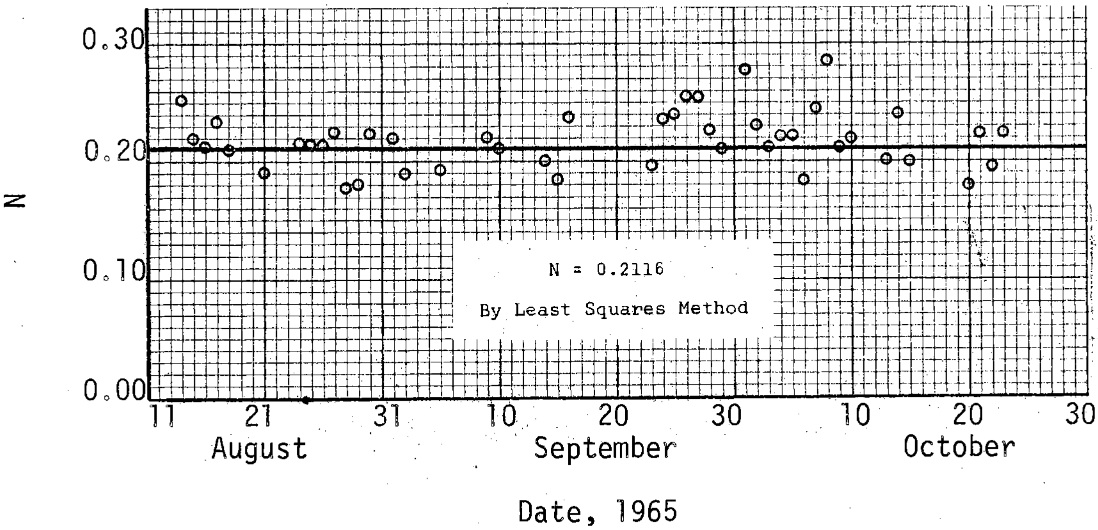


Figure 20. Daily Values of N for Mass Transfer Equation 99 for the Untreated Pond.

a pyranometer and a flat plate radiometer to measure incoming radiation. Outgoing radiation is estimated from reflectance equations and measured water surface temperature. Net radiation is the difference between incoming and outgoing radiation. The use of a net radiometer to measure net radiation would reduce the instrumentation needed and simplify the calculations necessary to arrive at estimated evaporation by the energy budget.

A net radiometer was placed over both the treated and untreated pond and net radiation measured for 12 days. Table XIX gives measured net radiation and net radiation from the energy budget for both ponds. A linear regression analysis comparing net radiation measured by the net radiometer with net radiation from the energy budget for the treated pond gave the equation

$$Q_{nT} = 76.77 + 0.66\ Q_{nEB} \tag{121}$$

where

Q_{nT} = net radiation measured by net radiometer over treated pond, cal/cm^2-day

Q_{nEB} = net radiation determined by energy budget, cal/cm^2-day

Deviation from regression was 16.58 calories with a correlation coefficient of 0.90. A similar analysis for the untreated pond gave the equation

$$Q_{nUT} = 94.84 + 0.63\ Q_{nEB} \tag{122}$$

where

Q_{nUT} = net radiation measured by net radiometer over untreated pond, cal/cm^2-day.

TABLE XIX

NET RADIATION BY NET RADIOMETERS AND ENERGY BUDGET, 1965

Date	Net Radiation			
	Treated Pond		Untreated Pond	
	Net Radiometer cal/cm^2 - day	Energy Budget cal/cm^2 - day	Net Radiometer cal/cm^2 - day	Energy Budget cal/cm^2 - day
8/15	304.6	362.7	324.1	381.7
8/16	317.2	388.3	333.0	413.1
8/17	398.4	480.2	417.4	513.7
8/18	410.4	484.5	430.7	529.1
8/21	324.3	405.2	354.5	440.7
8/24	351.2	435.0	377.4	470.4
8/25	392.5	472.8	416.0	511.4
8/26	383.4	453.3	407.3	488.5
8/27	313.3	339.9	339.5	377.1
8/28	355.0	369.7	389.6	408.4
8/29	344.8	428.0	389.4	468.4
8/30	382.8	466.0	414.3	501.2

Deviation from regression was 16.17 calories with a correlation coefficient of 0.91.

Net radiation measured by the net radiometers is compared with net radiations from the energy budget in Figure 21. The miniature net radiometers apparently did not accurately predict net radiation from the treated or untreated pond.

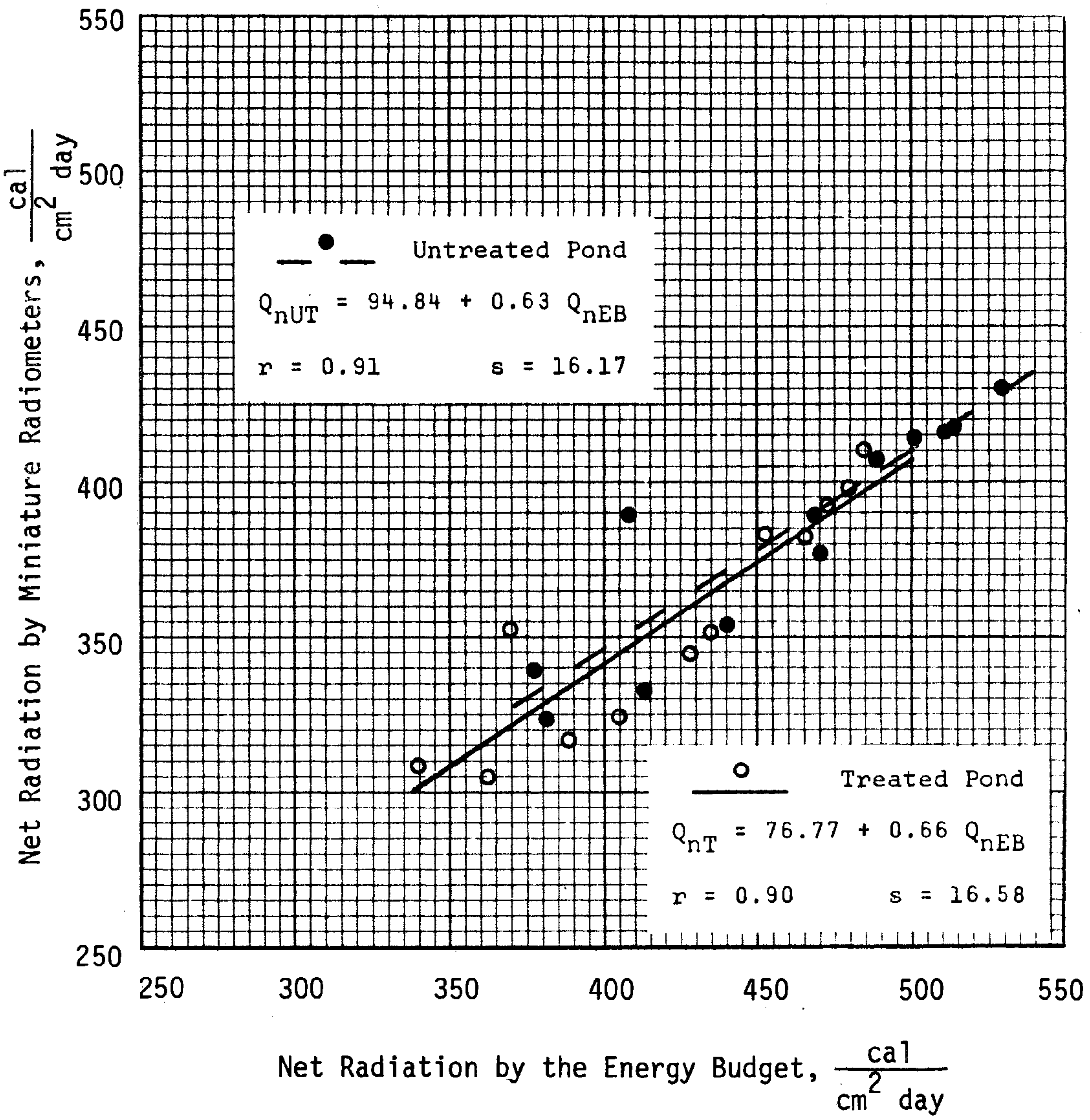


Figure 21. Comparison of Net Radiation Measured by the Miniature Net Radiometers with Net Radiation Determined by the Energy Budget for the Treated and Untreated Ponds.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

An evaporation study was conducted on paired ponds of approximately one-fourth acre surface area and six feet deep. The study was unique in that evaporation from a normal water surface was compared with evaporation from a water surface covered with a monolayer under identical atmospheric conditions. One pond served as a check throughout the study. A monolayer was maintained on the other pond by an automatic distribution system delivering monolayer forming chemical. The monolayer forming material was long chain alcohols in powdered form of the following composition: 2% C_{14}, 29% C_{16}, 61% C_{18}, 5% C_{20}, and 3% non-alcohol.

The objectives of this study were: 1) to develop heat and mass transfer equations with constant coefficients to determine evaporation from treated and untreated reservoirs, 2) to develop a procedure for estimating evaporation reduction by a monolayer based on heat and mass transfer equations, and 3) to compare the developed equations and procedure with presently used equations and procedures.

The experimental ponds were lined with plastic to prevent seepage and constructed so that no surface runoff water could enter. As a result, an accurate water budget was maintained to serve as a standard for evaluating evaporation equations.

A semi-empirical equation

$$E = \frac{0.2116}{T_o} D\, Sc^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} (e_o - e_2) - K_E \tag{99}$$

was developed for estimating evaporation from an untreated reservoir. The value of K_E is dependent on reservoir size, being -0.0031 for the one-fourth acre experimental pond and 0.0677 for Lake Hefner, a 2500 acre lake at Oklahoma City. Daily evaporation calculated by the above equation was in good agreement with evaporation measured by the water budget for both the experimental pond and Lake Hefner. The coefficient, 0.2116, was more nearly constant than the coefficient of the commonly used evaporation equation developed in the 1950-51 Lake Hefner investigations. By analogy, heat transfer from an untreated reservoir can be expressed by the equation

$$Q_h = 976.32\, k\, Pr^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} (T_o - T_2) - K_H \tag{100}$$

As the numerical value of K_E was small, K_E and K_H were taken as zero for the experimental ponds.

The mass transfer equation

$$E_T = \frac{e_o - e_2}{R_a + R_f} \tag{101}$$

where

$$R_a = \frac{1}{\frac{0.2116}{T_o} D\, Sc^{1/3} \left(\frac{u_2}{\nu}\right)^{0.78} - K_E} \tag{123}$$

and

$$R_f = \frac{e^{47.44 - \frac{10510}{T_o}}}{u_2^{1.674}} \tag{110}$$

was derived and found valid for estimating evaporation from the experimental pond covered with a monolayer. Heat transfer from the treated pond was determined by the same equation as for the untreated pond.

For the untreated pond, evaporation by the energy budget was in good agreement with evaporation by the water budget. Total evaporation for 45 days was 24.36 centimeters by the energy budget and 24.43 centimeters by the water budget.

Evaporation from the treated pond was greater by the energy budget than by the water budget. For 31 days, evaporation was 14.58 centimeters by the energy budget and 13.54 centimeters by the water budget. The greater evaporation by the energy budget was attributed to a significant energy loss as heat through the bottom of the treated pond.

Daily net change in stored energy in the treated pond was significantly different from that in the untreated pond.

The combined method developed by Harbeck and Koberg underestimated evaporation reduction by the monolayer. Estimated evaporation reduction due to the monolayer by the combined method was 4.85 centimeters for 31 days or 24.96 percent. Evaporation reduction by the water budget for the 31 days was 5.51 centimeters or 28.92 percent. The underestimate of evaporation reduction was attributed to the findings that: (1) the energy budget overestimated evaporation from the treated pond, and (2) the net change in stored energy was not the same for the treated and untreated ponds.

The combined method for estimating reduction in evaporation by a monolayer was modified. Evaporation from the treated pond was calculated by Equation 101 rather than by the energy budget. Equations 99 and 100 with K_E and K_H equal to zero replaced the heat and mass transfer equations developed in the 1950-1951 Lake Hefner investigation. Estimated evaporation reduction due to the monolayer by the modified combined method was 4.29 centimeters for 31 days or 23.86 percent. Evaporation reduction by the water budget for the 31 days was 5.51 centimeters or 28.92 percent. The underestimate of evaporation reduction due to the monolayer by the modified combined method was attributed to the finding that the net change in stored energy was not the same for the treated and untreated ponds.

Net radiation measured by the miniature radiometers was different from net radiation determined by the energy budget.

Conclusions

The following conclusions are based on the analysis and interpretation of the experimental results.

1. Evaporation from a reservoir can be expressed by Equation 99 with the numerical value of K_E dependent on reservoir size. By analogy, heat transfer from a reservoir can be expressed by Equation 123.
2. Evaporation from a reservoir covered with a monomolecular film can be expressed by Equation 101.
3. The resistance of a monolayer to evaporation is a function of water surface temperature and wind speed. The numerical values of the coefficients in Equation 110 are for the monolayer forming chemical used in this study.
4. The energy budget accurately predicted evaporation from a reservoir surface.

5. The energy budget overestimated evaporation from a reservoir covered with a monolayer. When a monolayer is applied, the water temperature in a reservoir increased resulting in a significant energy loss into the underlying soil. This loss cannot be neglected for a reservoir covered with a monolayer as is assumed in the energy budget.
6. Net change in stored energy in a reservoir was altered when a monolayer was applied.
7. The combined method underestimated evaporation reduction by a monolayer because the method neglected energy loss through the bottom of the reservoir and a change in stored energy when a monolayer was applied.
8. Evaporation reduction by the modified combined method gave results in agreement with the combined method. However, by neglecting the effect of a monolayer on change in stored energy, the method underestimated evaporation reduction by the monolayer.
9. The miniature net radiometers used in this study did not accurately measure net radiation reaching the pond surface.

Recommendations for Future Research

Based on the results of this study, the following research is suggested to improve the methods for predicting evaporation and its suppression by a monomolecular film.

1. A comprehensive study should be conducted to determine the effect of a water storage reservoir on the wind velocity profile and the water vapor profile above the earth's surface.

It has been observed that the wind velocity near the water surface and the vapor concentration of the air increase as an air mass travels across a water surface. Most attempts to quantify the developing boundary layer are based on model studies conducted in the laboratory. A field scale study is needed to measure the velocity and vapor boundary layer development across a reservoir.

2. Evaporation equations, based on mass transfer theory, should be re-evaluated with the parameters averaged over a time period of one hour or less. The parameters for these equations are commonly averaged for 24 hours or longer. However, the relationships between evaporation parameters are not necessarily linear.
3. A study should be conducted to measure the energy loss through the bottom of a reservoir covered with a monolayer. This study is needed to determine the validity of the energy budget for predicting evaporation from a reservoir covered with a monolayer.
4. A well instrumented study is recommended to verify the finding in this study that the net change in stored energy within a reservoir is affected by the presence of an evaporation suppressant.
5. Evaporation studies should be conducted on reservoirs of various sizes to evaluate the mass transfer equations developed in this study for predicting evaporation from an untreated reservoir covered with a monolayer.

A SELECTED BIBLIOGRAPHY

1. Adam, N. K. "The Evaporation of Water From Clean and Contaminated Surfaces." Journal of Physical Chemistry, Vol. 29 (1925), 610.

2. Anderson, E. R. "Energy-Budget Studies." Water-Loss Investigations: Lake Hefner Studies, Technical Report. United States Geological Survey Professional Paper 269, 1954, 71-119.

3. Angstrom, A. "Applications of Heat Radiation Measurements to the Problems of the Evaporation From Lakes and the Heat Convection at Their Surfaces." Geografiska Annaler, Band II, 1920, 237-252.

4. Archer, R. J. and V. K. La Mer. "The Rate of Evaporation of Water Through Fatty Acid Monolayers." Journal of Physical Chemistry, Vol. 59 (1955), 200-208.

5. Beard, J. T. and J. A. Wiebelt. "Reflectance of Film Covered Water Surfaces as Related to Evaporation Suppression" and "Reflectance of a Water Wave Surface as Related to Evaporation Suppression." Journal of Geophysical Research, Vol. 71, No. 16, 1966, 3835-3847.

6. Bigelow, F. H. "Studies of the Phenomena of Evaporation of Water Over Lakes and Reservoirs." United States Monthly Weather Review, Vol. 35 (1907), 311-316: Vol. 36 (1908), 437-445: Vol. 38(1910), 307-313.

7. Birge, R. T. "The 1944 Values of Certain Atomic Constants With Particular Reference to the Electronic Charge." American Journal of Physics, Vol. 13 (1945), 63-73.

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

9. Braslavskii, A. P. and Z. A. Vikulina. Evaporation Norms From Water Reservoirs. Translated From Russian, Israel Program for Scientific Translations, Jerusalem, 1963.

10. Colburn, A. P. "A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction." Transactions of the American Institute of Chemical Engineers, Vol. 29 (1963), 174-210.

11. Crow, F. R. "Reducing Reservoir Evaporation; Application of Surface Films Cuts Losses." Agricultural Engineering, Vol. 42 (1961), 240-243.

12. Crow, F. R. and E. R. Daniel. "Chemicals for Controlling Evaporation from Open Water Surfaces." Transactions of the American Society of Agricultural Engineers, Vol. 1, No. 1 (1958), 72-75.

13. Cummings, N. W. "The Relative Importance of Wind, Humidity, and Solar Radiation in Determining Evaporation From Lakes." Physical Review, Vol. 25 (1925), 721.

14. Cummings, N. W. "The Evaporation-Energy Equations and Their Practical Application." American Geophysical Union Transactions, Vol. 21 (1940), 512-522.

15. Cummings, N. W. and B. Richardson. "Evaporation From Lakes." Physical Review, Vol. 30 (1927), 527-534.

16. Dressler, Russell G. and Arnold G. Johanson. "Water Reservoir Evaporation Control." Chemical Engineering Progress, Vol. 54, No. 1 (1958), 66-69.

17. Eckert, E. R. G., and R. M. Drake, Jr. Heat and Mass Transfer. New York: McGraw-Hill Book Co., Inc., 1959.

18. Federal Council for Science and Technology Committee on Water Resources Research. "A Ten-Year Program of Federal Water Resources Research." Washington, D. C.: The United States Government Printing Office, 1966.

19. Fitzgerald, D. "Evaporation." American Society of Civil Engineers Transactions" Vol. 15, Part II (1886), 581-646.

20. Florey, Q. L., W. U. Garstka and L. O. Timblin, Jr. "Computation of Evaporation Savings." Water-Loss Investigations: Lake Hefner 1958 Evaporation Reduction Investigations, United States Department of the Interior, Bureau of Reclamation, Denver, Colorado, 1959, 37-42.

21. Fry, W. E. "Determination of Evaporation at Lake Hefner by Energy and Water Budget Methods - 1965." (unpublished M.S. thesis, Oklahoma State University, 1967).

22. Geiger, R. The Climate Near the Ground, Cambridge, Massachusetts: Harvard University Press, 1965.

23. Gunaji, N. N., B. A. Tschantz, W. W. G. Yeh and C. Morales. "Evaporation Reduction Investigation, Elephant Butte Reservoir, New Mexico 1963-1965." Technical Report No. 25, Engineering Experiment Station, New Mexico State University, University Park, New Mexico, 1965.

24. Harbeck, G. E., Jr. "Evaporation Research at Lake Hefner." American Water Works Association Journal, Vol. 44, No. 8 (August 1952), 701-706.

25. Harbeck, Jr., G. E. "General Description of Lake Hefner." Water-Loss Investigations: Lake Hefner Studies, Technical Report. United States Geological Survey Professional Paper 269, 1954, 5-9.

26. Harbeck, G. E, Jr. "A Practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass Transfer Theory." United States Geological Survey Professional Paper 272-E, 1962.

27. Harbeck, G. E., Jr. and G. E. Koberg. "A Method of Evaluating the Effect of a Monomolecular Film in Suppressing Reservoir Evaporation." Journal of Geophysical Research, Vol. 64 (1959), 89-93.

28. Harbeck, G. E., Jr., M. A. Kohler, G. E. Koberg and others. "Water-Loss Investigations: Lake Mead Studies." United States Geological Survey Professional Paper 298, 1958.

29. Hedestrand, Gunnar. "On the Influence of Thin Surface Films on the Evaporation of Water." Journal of Physical Chemistry, Vol. 28 (1924), 1244.

30. Heywood, G. S. P. "Wind Structure Near the Ground and its Relation to Temperature Gradient." Royal Meteorological Society, Quarterly Journal, Vol. 57 (1931), 433-455.

31. Himus, G. W. "The Evaporation of Water in Open Pans." Institution of Chemical Engineers Transactions, Vol. 7 (1929), 166-177.

32. Holzman, B. "The Heat-Balance Method for the Determination of Evaporation From Water-Surfaces." American Geophysical Union Transactions, Vol. 22 (1941), 655-659.

33. Horton, R. E. "A New Evaporation Formula Developed." Engineering News-Record, Vol. 78 (1917), 196-199.

34. Hughes, G. H. "Analysis of Techniques Used to Measure Evaporation From Salton Sea, California." United States Geological Survey Professional Paper 272-H, 1967.

35. Koberg, G. E. "Methods to Compute Long-Wave Radiation From the Atmosphere and Reflected Solar Radiation From a Water Surface." United States Geological Professional Paper 272-F, 1964, 107-112.

36. Kohler, M. A. "Lake and Pan Evaporation." Water-Loss Investigations: Lake Hefner Studies, Technical Report, United States Geological Survey Professional Paper 269, 1954, 127-148.

37. Kreith, F. Principles of Heat Transfer, Scranton, Pennsylvania: International Textbook Co., 1966.

38. Langmuir, I. and V. J. Schaefer. "Rates of Evaporation of Water Through Compressed Monolayers on Water." Journal Franklin Institute, Vol. 235 (1943), 119.

39. Langbein, W.B., C. H. Hains and R. C. Culler. "Hydrology of Stock-Water Reservoirs in Arizona." United States Geological Survey Circular 110, 1951.

40. Langbein, W.B. and J. V. B. Wells. "The Water in the River and Creeks." Water, The Yearbook of Agriculture. Washington, D. C.: The United States Government Printing Office, 1955, 52-62.

41. Linsley, Jr., R. K., M. A. Kohler and J. L. H. Paulhus. Hydrology for Engineers. New York: McGraw-Hill Book Company, Inc., 1958.

42. Mansfield, W. W. "Effect of Surface Films on the Evaporation of Water." Nature, Vol. 172, No. 4389 (1953), 1101.

43. Mansfield, W. W. "Influence of Monolayers on the Natural Rate of Evaporation of Water." Nature, Vol. 175, No. 4449 (1955), 247-249.

44. Mansfield, W. W. "The Influence of Monolayers on Evaporation From Water Storages." Australian Journal of Applied Science, Vol. 9 (1958), 245-254.

45. Marciano, J. J. and G. E. Harbeck, Jr. "Mass-Transfer Studies." Water-Loss Investigations: Lake Hefner Studies, Technical Report, United States Geological Survey Professional Paper 269, 1954, 46-70.

46. Millar, F. G. "Evaporation From Free Water Surfaces." Canadian Meteorological Memoirs, Vol. 1, No.2 (1937).

47. Mysels, K. J. "On Evaporation From Wind-Swept Surfaces." Science, Vol. 129 (1959), 38-39.

48. Richardson, B. "Evaporation as a Function of Insolation." American Society of Civil Engineers Transactions, Vol. 95 (1931), 996-1011.

49. Rideal, Eric K. "On the Influence of Thin Surface Films on the Evaporation of Water." Journal of Physical Chemistry, Vol. 29 (1925), 1585.

50. Roberts, W. J. "Reducing Water Vapor Transport with Monolayers." Retardation of Evaporation by Monolayers: Transport Processes. Edited by Victor K. La Mer. Academic Press: New York and London, 1962, 193-201.

51. Rohwer, C. "Evaporation From Free Water Surfaces." Technical Bulletin 271, United States Department of Agriculture, Washington, D. C., 1931.

52. Runkles, J. R., J. F. Bartholic and R. I. Papendick. "Evaporation Reduction Investigations Pactola Reservoir, South Dakota, 1962-1963." Technical Bulletin 24, Agricultural Experiment Station, South Dakota State University, 1964.

53. Schlichting, H. Boundary Layer Theory. Translated by J. Kestin. New York: McGraw-Hill Book Company, Inc., 1960.

54. Schmidt, W. "Strahlung und Verdunstung in Freien Wasserflachen; ein Beitrage zum Warmehaushalt des Weltmeers und zum Wasserhaushalt der Erde." Annalen der Hydrographie und Maritimen Meteorologie, Vol. 34 (1915), 111-124, 169-178.

55. Silveston, P. L. "Economics of Water Conservation with Monomolecular Films." Transactions of the American Society of Agricultural Engineers, Vol. 8, No. 1 (1965), 127-137.

56. Sleight, R. B. "Evaporation From the Surface of Water and River-Bed Materials." Journal of Agricultural Research, Vol. 10 (1917), 209-262.

57. Smithsonian Meteorological Tables, prepared by R. J. List. Smithsonian Miscellaneous Collection, V. 114, Washington: Smithsonian Institution, 1951.

58. Snedecor, G. W. Statistical Methods, 5th ed. The Iowa State College Press, Ames, Iowa. (1956).

59. Sutton, O. G. "Note on the variation of the Wind with Height." Royal Meteorological Society, Quarterly Journal, Vol. 58 (1932).

60. Sutton, O. G. Atmospheric Turbulence. London: Methuen and Co. LTD., 1949.

61. Sverdrup, H. U. "On the Evaporation From the Oceans." Journal of Marine Research, Vol. 1, No. 1 (1937-1938), 3-14.

62. Sverdrup, H. U. "On the Annaul and Diurnal Variation of the Evaporation From the Oceans." Journal of Marine Research, Vol. 3, No. 2 (1940), 93-104.

63. Timblin, L. O., Jr., Q. L. Florey, and W. U. Garstka. "Laboratory and Field Reservoir Evaporation by the Bureau of Reclamation." Retardation of Evaporation by Monolayers: Transport Processes. Edited by Victor K. La Mer. Academic Press: New York and London, 1962, 177-192.

64. Vines, R. G. "Reducing Evaporation with Cetyl Alcohol Films: A New Method of Treating Large Water Storages." *Australian Journal of Applied Science*, Vol. 11, No. 1 (March, 1960), 200-204.

65. Vines, R. G. "Evaporation Control: A New Method of Treating Large Water Storages." *Retardation of Evaporation by Monolayers: Transport Processes*. Edited by Victor K. La Mer. Academic Press: New York and London, 1962, 137-160.

66. *Water-Loss Investigations: Lake Hefner Studies, Base Data Report*. United States Geological Survey Professional Paper 270, 1954.

APPENDIX A

HOURLY WIND VELOCITY

TABLE XX

HOURLY WIND VELOCITY IN CENTIMETERS PER SECOND

DATE	PER	HOUR INTERVAL											
		08-09	09-10	10-11	11-12	12-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
081365	N	272.69	281.64	299.52	308.46	259.28	236.93	227.99	254.81	214.58	236.93	272.69	254.81
081465	D	286.11	286.11	326.34	411.28	415.75	406.81	438.10	375.51	388.92	321.87	442.57	397.87
081465	N	156.46	120.70	71.53	120.70	165.40	98.35	143.05	147.52	84.94	80.47	116.23	80.47
081565	D	111.76	317.40	388.92	415.75	339.75	429.16	482.80	402.34	272.69	116.23	362.10	388.92
081565	N	339.75	303.99	299.52	272.69	236.93	223.52	236.93	241.40	125.17	107.29	169.88	174.35
081665	D	259.28	281.64	353.16	420.22	402.34	402.34	402.34	384.45	397.87	362.10	371.04	299.52
081665	N	232.46	259.28	232.46	205.64	223.52	201.17	174.35	201.17	187.76	196.70	178.82	295.05
081765	D	362.10	388.92	384.45	518.57	473.86	487.27	503.63	536.45	585.62	581.15	447.04	388.92
081765	N	366.57	312.93	263.75	286.11	330.81	308.46	286.11	272.69	223.52	223.52	169.88	259.28
081865	D	464.92	549.86	554.33	523.04	451.51	567.74	518.57	496.21	460.45	478.33	402.34	290.58
081865	N	192.23	151.99	125.17	156.46	165.40	165.40	219.05	187.76	165.40	281.64	312.93	393.40
081965	D	616.92	639.27	612.44	581.15	563.27	527.51	531.98	527.51	509.63	469.39	424.69	406.81
082065	N	165.40	187.76	205.64	102.82	120.70	116.23	156.46	169.88	210.11	219.05	138.58	169.88
082165	D	245.87	151.99	129.64	111.76	156.46	165.40	125.17	250.34	138.58	134.11	84.94	120.70
082365	N	160.93	187.76	174.35	187.76	219.05	232.46	214.58	165.40	147.52	169.88	107.29	201.17
082465	D	160.93	201.17	201.17	192.23	277.16	379.98	433.63	397.87	388.92	406.81	321.87	254.81
082465	N	268.22	299.52	353.16	326.34	268.22	281.64	295.05	254.81	303.99	286.11	299.52	366.57
082565	D	357.63	388.92	348.69	411.28	482.80	496.21	496.21	478.33	487.27	500.68	344.22	272.69
082565	N	348.69	420.22	455.98	505.16	509.63	496.21	478.33	451.51	393.40	447.04	464.92	505.16
082665	D	482.80	487.27	473.86	491.74	518.57	531.98	496.21	599.03	612.44	567.74	442.57	366.57
082665	N	379.98	420.22	321.87	411.28	366.57	388.92	406.81	388.92	357.63	272.69	138.58	295.05
082765	D	366.57	460.45	473.86	393.40	362.10	388.92	411.28	621.39	907.49	433.63	259.28	120.70
082765	N	178.82	223.52	210.11	120.70	219.05	174.35	80.47	76.00	183.29	223.52	344.22	415.75
082865	D	451.51	406.81	384.45	375.51	348.69	348.69	295.05	366.57	388.92	371.04	312.93	223.52
082865	N	223.52	178.82	223.52	178.82	125.17	178.82	214.58	151.99	236.93	236.93	223.52	339.75
082965	D	482.80	500.68	509.63	563.27	572.21	567.74	572.21	594.56	563.27	554.33	469.39	379.98
082965	N	375.51	397.87	339.75	375.51	487.27	424.69	411.28	464.92	411.28	303.99	353.16	438.10
083065	D	545.39	634.80	648.21	710.79	697.38	724.20	728.68	706.32	701.85	706.32	514.10	406.81
083165	N	353.16	245.87	295.05	268.22	375.51	326.34	201.17	93.88	80.47	84.94	111.76	134.11
090165	D	160.93	138.58	187.76	223.52	214.58	245.87	272.69	210.11	210.11	268.22	205.64	129.64
090165	N	120.70	147.52	120.70	49.17	31.29	26.82	53.64	107.29	160.93	210.11	268.22	290.58
090265	D	447.04	536.45	523.04	518.57	536.45	554.33	536.45	549.86	567.74	527.51	433.63	268.22
090465	N	178.82	214.58	219.05	196.70	174.35	223.52	178.82	192.23	286.11	281.64	312.93	330.81
090565	D	442.57	487.27	514.10	590.09	581.15	527.51	527.51	451.51	451.51	388.92	388.92	339.75
090865	N	254.81	245.87	187.76	169.88	241.40	286.11	308.46	241.40	143.05	219.05	201.17	254.81
090965	D	402.34	482.80	527.51	460.45	420.22	415.75	402.34	362.10	366.57	362.10	295.05	254.81
090965	N	272.69	299.52	254.81	232.46	116.23	58.12	134.11	120.70	111.76	219.05	205.64	344.22
091065	D	549.86	715.26	679.50	554.33	616.92	599.03	545.39	514.10	585.62	625.86	545.39	612.44
091365	N	236.93	183.29	187.76	53.64	80.47	89.41	125.17	348.69	420.22	344.22	286.11	303.99
091465	D	366.57	554.33	715.26	782.32	782.32	724.20	639.27	460.45	438.10	353.16	102.82	53.64
091465	N	402.34	397.87	473.86	464.92	397.87	344.22	326.34	429.16	509.63	540.92	473.86	514.10
091565	D	469.39	424.69	317.40	397.87	438.10	505.16	567.74	675.03	675.03	514.10	447.04	500.68
091565	N	482.80	545.39	469.39	523.04	536.45	478.33	455.98	362.10	317.40	393.40	540.92	652.68
091665	D	724.20	751.03	773.38	804.67	777.85	773.38	768.91	621.39	621.39	621.39	621.39	621.39
092265	N	116.23	80.47	71.53	62.59	22.35	26.82	35.76	44.70	62.59	160.93	281.64	339.75
092365	D	424.69	473.86	491.74	491.74	460.45	505.16	545.39	545.39	558.80	625.86	616.92	514.10
092365	N	563.27	496.21	375.51	339.75	277.16	277.16	236.93	272.69	219.05	223.52	183.29	192.23
092465	D	210.11	120.70	143.05	125.17	143.05	143.05	187.76	125.17	201.17	160.93	151.99	134.11
092465	N	89.41	67.06	93.88	120.70	125.17	102.82	102.82	107.29	116.23	111.76	165.40	214.58
092565	D	281.64	326.34	384.45	384.45	308.46	371.04	447.04	447.04	429.16	272.69	196.70	219.05
092565	N	250.34	286.11	371.04	379.98	335.28	312.93	321.87	335.28	272.69	268.22	205.64	259.28
092665	D	232.46	120.70	98.35	165.40	196.70	254.81	250.34	317.40	308.46	268.22	268.22	299.52
092665	N	299.52	312.93	339.75	326.34	326.34	254.81	290.58	272.69	254.81	241.40	250.34	277.16
092765	D	366.57	433.63	460.45	429.16	433.63	397.87	397.87	379.98	362.10	281.64	201.17	187.76
092765	N	192.23	299.52	321.87	268.22	178.82	165.40	196.70	192.23	241.40	272.69	232.46	254.81
092865	D	388.92	415.75	469.39	397.87	384.45	388.92	406.81	411.28	393.40	295.05	250.34	254.81
092865	N	227.99	201.17	210.11	205.64	192.23	299.52	326.34	299.52	254.81	286.11	272.69	339.75
092965	D	393.40	451.51	514.10	581.15	523.04	581.15	581.15	585.62	491.74	393.40	308.46	371.04
092965	N	420.22	447.04	330.81	442.57	670.56	599.03	563.27	527.51	590.09	648.21	540.92	509.63
093065	D	670.56	670.56	670.56	625.86	576.68	585.62	572.21	576.68	514.10	424.69	236.93	102.82
093065	N	58.12	53.64	98.35	84.94	98.35	93.88	53.64	67.06	84.94	138.58	116.23	98.35
100165	D	160.93	205.64	312.93	259.28	281.64	236.93	245.87	219.05	165.40	80.47	26.82	67.06
100165	N	44.70	40.23	31.29	44.70	53.64	58.12	84.94	40.23	31.29	62.59	35.76	44.70
100265	D	156.46	236.93	259.28	303.99	312.93	263.75	250.34	245.87	183.29	138.58	129.64	151.99
100265	N	129.64	58.12	31.29	26.82	31.29	35.76	40.23	17.88	17.88	53.64	53.64	35.76
100365	D	80.47	93.88	80.47	210.11	147.52	192.23	223.52	201.17	156.46	84.94	40.23	53.64
100365	N	143.05	67.06	40.23	76.00	58.12	67.06	76.00	49.17	102.82	49.17	31.29	76.00
100465	D	147.52	169.88	187.76	303.99	196.70	156.46	138.58	89.41	183.29	138.58	89.41	80.47
100465	N	76.00	58.12	58.12	49.17	22.35	49.17	76.00	67.06	120.70	62.59	102.82	116.23
100565	D	192.23	210.11	201.17	268.22	357.63	272.69	192.23	205.64	210.11	348.69	308.46	245.87
100565	N	268.22	250.34	236.93	245.87	236.93	111.76	125.17	205.64	143.05	93.88	49.17	116.23
100665	D	254.81	424.69	326.34	335.28	362.10	326.34	214.58	192.23	156.46	76.00	102.82	134.11
100665	N	174.35	107.29	102.82	165.40	138.58	192.23	178.82	201.17	223.52	272.69	227.99	236.93
100765	D	371.04	536.45	527.51	545.39	491.74	509.63	585.62	594.56	567.74	339.75	326.34	210.11
100765	N	156.46	93.88	111.76	156.46	147.52	151.99	129.64	116.23	98.35	84.94	129.64	76.00
100865	D	49.17	71.53	98.35	165.40	143.05	187.76	196.70	147.52	174.35	93.88	89.41	76.00
100865	N	84.94	116.23	89.41	76.00	35.76	93.88	111.76	71.53	26.82	84.94	107.29	89.41
100965	D	147.52	201.17	236.93	303.99	438.10	447.04	366.57	308.46	174.35	111.76	143.05	156.46
100965	N	116.23	93.88	67.06	40.23	44.70	58.12	67.06	67.06	62.59	58.12	26.82	49.17
101065	D	151.99	174.35	210.11	263.75	344.22	366.57	464.92	321.87	183.29	201.17	205.64	268.22
101165	N	129.64	156.46	143.05	143.05	143.05	147.52	129.64	71.53	76.00	71.53	58.12	31.29
101265	D	62.59	192.23	263.75	241.40	241.40	277.16	245.87	236.93	245.87	196.70	169.88	84.94
101265	N	160.93	192.23	147.52	89.41	120.70	165.40	147.52	196.70	143.05	138.58	178.82	169.88
101365	D	277.16	286.11	335.28	335.28	335.28	366.57	366.57	388.92	348.69	268.22	259.28	281.64
101365	N	348.69	312.93	272.69	326.34	303.99	330.81	295.05	308.46	402.34	438.10	397.87	451.51
101465	D	500.68	625.86	670.56	661.62	567.74	576.68	545.39	442.57	339.75	299.52	286.11	295.05
101465	N	295.05	295.05	335.28	335.28	321.87	321.87	241.40	93.88	102.82	125.17	210.11	223.52
101565	D	393.40	478.33	487.27	402.34	254.81	344.22	478.33	406.81	379.98	321.87	326.34	312.93
101565	N	263.75	272.69	303.99	326.34	388.92	388.92	384.45	406.81	451.51	397.87	388.92	406.81
101665	D	478.33	500.68	572.21	514.10	500.68	438.10	433.63	438.10	406.81	353.16	272.69	308.46
101665	N	362.10	366.57	420.22	303.99	321.87	326.34	286.11	250.34	272.69	263.75	259.28	245.87
101765	D	339.75	496.21	536.45	536.45	514.10	491.74	509.63	531.98	478.33	379.98	321.87	353.16
101865	N	259.28	259.28	259.28	254.81	254.81	254.81	254.81	254.81	254.81	254.81	254.81	254.81
101965	D	254.81	254.81	254.81	254.81	254.81	254.81	254.81	254.81	254.81	259.28	259.28	259.28
101965	N	303.99	303.99	303.99	303.99	303.99	303.99	303.99	303.99	299.52	299.52	299.52	299.52
102065	D	299.52	299.52	299.52	299.52	303.99	303.99	303.99	303.99	303.99	303.99	303.99	303.99
102065	N	491.74	491.74	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21
102165	D	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21	496.21	491.74	491.74
102165	N	286.11	286.11	286.11	286.11	286.11	286.11	286.11	281.64	281.64	281.64	281.64	281.64
102265	D	281.64	281.64	281.64	281.64	286.11	286.11	286.11	286.11	286.11	286.11	286.11	286.11
102265	N	272.69	272.69	272.69	272.69	272.69	268.22	268.22	268.22	268.22	268.22	268.22	268.22
102365	D	268.22	268.22	268.22	268.22	268.22	268.22	268.22	268.22	272.69	272.69	272.69	272.69

N REFERS TO NIGHT TIME HOURS; D REFERS TO DAYLIGHT HOURS

APPENDIX B

HOURLY DRY BULB AIR TEMPERATURE

HOURLY WET BULB AIR TEMPERATURE

TABLE XXI

HOURLY DRY BULB AIR TEMPERATURE IN DEGREES CENTIGRADE

DATE	PER	HOUR INTERVAL 08-09	09-10	10-11	11-12	12-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
081365	N	27.49	26.51	25.63	24.79	23.66	22.89	22.24	21.65	21.06	20.55	20.72	22.59
081465	D	25.01	27.29	29.68	31.07	31.29	32.24	32.63	32.45	32.70	31.03	28.48	24.01
081465	N	22.86	23.34	23.21	22.51	22.44	21.71	21.65	21.85	21.45	21.34	22.57	23.76
081565	D	24.46	27.03	27.89	28.47	29.60	30.28	28.05	26.06	26.89	27.02	24.93	23.14
081565	N	22.29	21.63	21.02	20.51	20.18	20.20	20.42	20.38	20.09	20.16	20.17	21.26
081665	D	23.01	23.71	24.51	25.87	27.78	29.38	30.33	30.86	30.29	30.07	28.64	26.38
081665	N	25.13	24.31	23.69	23.31	22.60	21.89	21.48	21.11	21.02	20.77	21.09	23.13
081765	D	26.06	29.12	31.75	33.80	33.98	35.08	35.07	35.36	35.43	33.76	32.33	30.59
081765	N	29.40	27.91	27.01	26.39	25.48	24.97	24.61	24.23	23.60	23.39	23.52	25.92
081865	D	28.32	30.91	32.58	33.90	34.96	35.74	35.68	35.67	35.37	34.40	33.29	31.01
081865	N	26.85	25.99	26.43	26.29	25.54	24.88	25.16	25.22	23.89	23.30	23.43	24.33
081965	D	24.65	25.16	27.76	28.81	30.29	31.02	31.30	31.52	31.59	30.27	27.99	26.56
082065	N	23.90	23.36	22.98	22.72	22.48	22.43	23.03	22.72	21.94	21.70	21.63	23.65
082165	D	25.68	27.89	29.95	31.43	32.74	34.06	33.32	31.63	32.51	32.87	31.83	30.47
082365	N	27.09	26.08	25.24	24.64	24.27	23.98	23.03	22.30	21.88	21.55	21.88	22.75
082465	0	24.18	25.37	26.98	29.06	30.70	31.62	32.44	32.44	32.57	32.13	30.87	29.36
082465	N	28.22	27.64	26.91	26.44	25.73	25.04	24.14	23.34	22.91	22.34	22.64	23.97
082565	D	26.27	29.55	32.05	34.20	35.19	35.77	36.21	36.30	36.13	35.12	33.75	31.68
082565	N	30.37	29.60	29.08	28.56	28.23	27.67	27.07	26.40	25.69	25.00	25.34	26.93
082665	D	29.22	31.61	33.46	35.13	36.22	37.43	37.42	36.90	36.11	35.79	34.28	32.69
082665	N	31.25	30.71	29.90	29.17	28.40	27.85	27.45	26.84	26.09	25.44	25.33	26.87
082765	D	28.81	31.36	32.42	34.58	36.22	37.57	37.58	35.14	29.53	27.49	26.10	25.18
082765	N	24.34	24.18	22.89	21.69	21.30	20.73	20.21	19.76	19.56	19.40	19.74	20.72
082865	0	22.10	23.80	25.30	26.53	27.79	28.76	29.35	29.88	29.45	28.77	27.59	24.59
082865	N	23.24	22.28	22.10	21.37	20.76	20.25	20.31	20.05	20.03	19.95	21.00	23.49
082965	D	26.06	27.77	29.38	30.06	30.86	31.73	32.34	32.47	32.64	31.94	30.67	29.07
082965	N	28.04	27.30	26.52	25.92	25.77	25.24	24.76	24.39	24.13	23.79	23.94	25.50
083065	D	27.73	29.73	31.08	32.02	32.81	33.10	33.38	33.30	33.24	32.46	31.46	30.10
083165	N	18.45	17.12	16.02	15.30	14.90	14.52	14.21	13.75	13.16	12.65	12.82	15.34
090165	D	17.58	19.64	22.03	23.66	24.52	25.51	25.66	25.86	26.06	25.34	23.99	22.63
090165	N	21.42	20.31	18.83	18.05	17.63	17.05	15.56	15.01	14.69	14.96	15.19	17.05
090265	D	19.77	21.79	23.61	24.63	25.98	26.57	27.04	27.28	27.25	26.36	25.04	23.66
090465	N	28.12	27.48	26.70	25.74	25.49	25.25	24.44	22.43	21.92	21.85	22.25	23.72
090565	D	25.49	26.92	28.06	28.92	29.61	30.47	31.12	32.15	32.52	31.21	29.68	28.32
090865	N	27.89	26.99	25.98	24.91	24.21	23.55	23.07	22.62	22.31	22.09	22.02	23.15
090965	D	26.16	28.30	30.01	31.55	32.32	33.18	33.74	33.91	33.69	32.44	30.67	28.86
090965	N	27.97	26.54	26.02	25.36	24.33	22.78	22.32	21.22	20.55	20.98	20.84	22.67
091065	D	25.27	26.56	27.74	28.88	25.66	27.05	28.46	29.12	28.64	26.37	24.57	23.19
091365	N	30.46	29.44	28.60	27.22	27.34	27.30	26.31	27.24	26.84	26.55	26.10	27.37
091465	D	30.06	32.59	34.74	36.65	38.14	38.96	38.51	38.20	37.40	35.63	32.98	33.42
091465	N	30.14	27.59	27.05	26.04	24.82	24.07	23.02	22.81	22.49	22.03	22.01	22.80
091565	0	24.26	25.98	28.42	31.20	33.46	34.67	35.83	36.69	37.28	35.68	33.91	32.53
091565	N	30.96	30.15	29.42	28.70	27.69	26.99	26.63	25.90	25.18	25.10	25.34	26.17
091665	D	27.36	28.87	30.46	31.64	32.44	33.28	33.92	34.07	34.37	33.27	32.12	30.77
092265	N	18.99	17.82	17.39	16.83	16.39	15.47	14.35	14.34	13.03	13.02	13.70	14.75
092365	D	15.64	17.20	18.82	19.98	19.97	20.35	19.98	19.40	17.92	16.11	13.94	12.78
092365	N	12.52	11.79	11.25	11.14	10.89	10.81	10.40	10.28	10.04	9.60	9.82	10.13
092465	D	10.42	10.99	12.02	12.67	13.41	14.54	15.60	15.82	17.30	14.78	12.72	11.95
092465	N	11.45	11.97	12.39	12.37	12.00	12.10	12.25	12.31	12.24	12.29	12.32	12.46
092565	D	12.86	13.37	14.25	14.90	15.31	16.37	18.01	18.72	18.96	18.70	18.00	17.54
092565	N	17.27	17.13	16.98	17.06	16.40	15.75	15.29	15.03	14.90	14.64	14.21	15.13
092665	D	16.75	18.43	19.64	20.12	20.59	21.51	22.60	23.96	24.57	23.26	21.00	19.99
092665	N	19.13	18.41	18.11	17.70	17.12	16.48	16.36	15.88	15.16	14.40	14.09	15.04
092765	0	17.79	19.73	20.69	21.62	22.70	23.72	24.54	25.31	25.28	23.57	22.10	20.99
092765	N	19.59	18.75	18.40	17.40	16.42	15.83	15.27	15.17	14.93	14.78	14.62	15.50
092865	D	18.27	20.17	21.77	23.50	24.61	25.38	26.17	26.96	26.97	25.35	23.46	22.05
092865	N	20.81	19.72	19.27	18.46	18.09	18.36	18.36	17.88	17.17	16.47	16.25	17.07
092965	D	19.38	21.39	23.09	24.20	24.98	25.82	26.53	27.32	27.13	25.15	23.86	22.90
092965	N	21.55	20.23	19.66	18.60	12.85	11.14	10.71	10.59	10.24	9.92	9.42	9.62
093065	D	11.34	11.50	11.64	12.10	13.53	13.45	13.39	13.85	14.61	13.69	12.07	10.49
093065	N	10.25	9.89	8.59	8.01	7.78	7.46	7.66	7.52	7.14	6.42	6.80	8.57
100165	D	12.89	15.77	17.51	17.92	19.00	19.71	20.53	21.16	20.60	19.17	17.76	15.77
100165	N	13.02	12.71	11.13	10.54	9.43	8.16	8.37	8.58	7.74	7.08	7.66	9.96
100265	D	13.53	16.81	18.79	20.51	21.15	22.05	22.30	22.62	22.11	20.89	19.17	17.20
100265	N	16.68	15.35	13.87	13.40	12.11	11.42	11.58	11.04	11.03	9.00	9.14	10.35
100365	D	12.41	14.38	16.03	18.90	19.20	19.94	19.86	19.54	19.33	18.69	18.07	17.34
100365	N	17.60	16.81	16.02	15.71	15.17	14.35	14.41	14.30	13.66	14.01	13.88	13.98
100465	D	15.00	15.72	16.46	18.14	18.79	19.59	20.28	19.90	18.96	17.89	16.34	16.09
100465	N	15.47	14.82	14.17	13.11	12.89	12.16	10.90	11.43	11.83	11.62	11.66	12.98
100565	D	14.61	16.55	18.06	19.49	20.22	19.17	18.92	18.55	18.34	17.40	15.24	13.94
100565	N	13.61	13.54	12.74	12.13	11.59	10.93	10.32	10.49	10.26	10.05	10.22	11.30
100665	D	13.03	14.01	14.16	16.70	17.96	18.33	19.02	20.30	20.67	19.83	17.66	15.98
100665	N	15.08	14.22	13.36	13.11	12.28	12.27	12.33	12.19	12.23	12.43	12.38	13.66
100765	D	18.33	21.10	23.89	25.32	26.25	28.02	29.16	29.51	28.90	25.51	21.85	18.92
100765	N	17.64	16.52	15.37	14.38	12.47	12.19	11.90	11.34	11.28	10.93	10.71	12.19
100865	D	17.00	20.27	23.50	24.68	25.62	26.95	27.64	27.70	27.33	25.30	23.24	20.24
100865	N	18.45	17.04	16.52	15.67	15.37	14.02	13.31	13.83	13.25	13.14	11.47	13.90
100965	D	18.12	21.27	24.27	26.54	29.64	31.46	33.28	33.18	31.91	28.76	24.89	22.55
100965	N	20.78	19.47	17.85	16.54	14.73	14.21	12.89	11.72	12.70	12.21	11.64	13.09
101065	D	17.20	20.10	25.51	29.29	32.16	33.36	34.30	33.57	31.97	29.52	27.39	25.68
101165	N	10.82	9.84	9.23	8.46	7.78	6.93	6.61	5.80	4.92	4.61	4.50	6.28
101265	D	10.64	13.39	15.37	16.59	17.40	18.28	19.23	19.91	19.69	18.46	17.56	16.76
101265	N	16.53	15.99	16.00	16.07	15.89	15.18	14.06	13.53	13.84	13.39	12.46	12.99
101365	D	16.26	18.19	20.57	22.32	24.27	25.74	26.28	26.60	26.07	24.44	22.81	21.69
101365	N	20.46	19.67	18.93	18.63	18.22	18.07	18.28	18.19	18.11	18.11	18.15	18.88
101465	D	20.26	22.21	23.72	24.39	23.99	25.03	25.90	25.09	24.83	24.67	23.94	22.61
101465	N	22.07	21.22	20.60	20.34	19.97	19.94	19.69	18.20	18.11	16.97	17.75	17.96
101565	D	19.56	21.11	21.89	21.95	23.29	25.49	25.18	24.28	24.38	23.17	22.49	22.35
101565	N	21.65	20.88	21.14	21.32	21.22	20.85	20.61	20.95	20.96	20.79	20.98	21.15
101665	D	21.76	22.64	23.78	24.68	24.39	25.09	26.70	27.22	26.43	25.36	24.46	23.79
101665	N	23.41	22.80	22.22	21.09	20.32	19.89	19.55	19.13	19.00	18.53	18.31	18.18
101765	D	19.45	21.88	23.15	24.56	25.46	26.22	26.91	26.58	25.83	24.79	23.96	23.32
101865	N	17.50	17.36	17.07	16.99	16.94	16.91	16.81	16.23	16.10	16.33	15.72	15.89
101965	D	16.49	17.82	19.22	20.70	21.72	22.85	22.97	23.04	22.56	19.61	17.02	15.58
101965	N	14.98	13.65	12.61	11.91	11.62	11.10	10.38	9.64	9.06	8.67	8.82	10.73
102065	D	13.38	15.12	17.92	19.24	20.44	20.88	21.17	20.02	18.36	16.74	14.32	12.42
102065	N	11.66	12.01	11.92	11.19	10.59	10.28	9.40	8.55	7.71	7.21	7.07	8.74
102165	D	10.00	10.96	12.29	14.17	15.68	16.81	17.24	17.14	16.29	14.26	12.38	11.20
102165	N	10.21	9.26	8.66	8.26	7.86	7.01	5.08	4.63	4.12	2.96	2.71	5.47
102265	D	8.80	11.55	14.04	16.01	17.48	18.61	19.62	19.53	17.60	15.77	14.26	12.89
102265	N	12.06	10.88	9.52	9.20	9.09	9.22	9.17	9.00	8.84	9.76	10.02	11.20
102365	D	13.94	16.99	18.61	21.05	22.62	23.12	23.31	22.97	22.11	19.14	16.61	15.42

N REFERS TO NIGHT TIME HOURS; D REFERS TO DAYLIGHT HOURS

TABLE XXII

HOURLY WET BULB AIR TEMPERATURE IN DEGREES CENTIGRADE

DATE	PER	HOUR INTERVAL											
		08-09	09-10	10-11	11-12	12-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
081365	N	20.48	20.10	19.79	19.58	19.43	19.36	19.22	19.08	18.96	18.85	18.90	19.68
081465	D	20.52	21.04	21.64	23.46	25.95	25.46	23.83	23.18	23.36	24.73	23.16	19.96
081465	N	19.45	19.79	19.84	19.43	19.39	19.12	18.96	19.18	19.06	19.11	19.93	20.27
081565	D	20.61	21.59	21.93	22.00	21.77	22.91	22.27	21.91	21.01	21.08	21.88	21.37
081565	N	20.80	20.56	19.98	19.75	19.56	19.51	19.57	19.47	19.21	19.25	19.30	19.92
081665	D	20.52	21.03	21.49	21.94	22.27	22.37	22.16	21.63	21.47	21.52	21.46	21.41
081665	N	21.45	21.35	21.14	21.09	20.91	20.66	20.50	20.45	20.36	20.15	20.12	20.89
081765	D	21.66	23.06	24.61	22.75	23.50	24.22	24.15	24.36	24.79	24.99	23.98	22.59
081765	N	22.18	21.89	21.58	21.35	21.07	20.46	20.03	19.79	19.52	19.36	19.54	20.71
081865	D	21.66	22.13	22.76	23.27	23.53	22.97	23.02	22.92	22.83	22.86	22.72	22.65
081865	N	21.81	21.33	21.59	21.73	21.52	21.32	21.29	21.23	20.94	21.11	21.34	21.78
081965	D	21.84	21.83	22.66	23.08	23.42	23.43	23.56	23.47	23.68	23.32	22.56	21.63
082065	N	21.41	21.13	21.11	21.00	20.99	20.85	21.11	20.78	20.40	20.50	20.78	21.60
082165	D	22.40	22.65	22.95	23.41	23.69	23.97	23.35	23.47	23.37	23.30	23.41	23.15
082365	N	23.33	22.82	22.83	22.69	22.46	22.06	21.71	21.37	21.12	20.85	21.04	21.51
082465	D	22.04	22.56	23.23	23.78	24.38	24.84	24.82	24.81	24.80	24.73	24.42	23.59
082465	N	23.28	23.11	23.14	23.01	22.48	21.92	21.36	20.93	20.83	20.67	20.78	21.39
082565	D	22.46	23.82	24.59	25.49	25.74	25.82	25.79	25.59	25.39	25.32	24.96	24.54
082565	N	24.33	24.31	24.13	23.80	23.35	22.97	22.67	22.40	22.19	21.92	22.01	22.64
082665	D	23.24	23.97	24.70	25.32	25.47	25.25	25.92	24.72	24.38	24.30	24.08	23.57
082665	N	23.17	23.25	23.19	22.74	22.32	22.07	22.08	21.85	21.50	21.24	21.29	21.96
082765	D	22.59	23.38	23.71	24.18	24.19	25.36	26.01	27.43	25.10	21.68	21.71	21.56
082765	N	21.70	21.36	20.90	20.62	20.39	20.09	19.76	19.38	19.37	19.20	19.28	19.46
082865	D	19.35	20.09	21.06	21.63	22.30	22.55	22.69	22.89	22.71	22.16	21.30	19.56
082865	N	19.07	18.56	18.64	18.31	17.94	17.94	18.32	18.33	18.67	19.02	19.79	21.44
082965	D	22.51	23.22	23.61	24.13	24.77	25.43	24.86	24.27	24.11	23.81	23.40	22.86
082965	N	22.63	22.59	22.54	22.49	22.26	22.14	21.98	21.67	21.57	21.32	21.35	22.00
083065	D	22.20	22.61	23.13	23.29	23.04	23.75	24.13	25.19	25.24	25.00	23.28	22.86
083165	N	17.69	16.75	15.67	14.89	14.31	14.10	13.79	13.31	12.71	12.29	12.31	14.10
090165	D	15.34	16.56	16.90	16.30	16.28	16.27	16.34	16.57	16.25	16.31	16.12	16.11
090165	N	15.89	15.36	14.79	14.45	14.35	14.02	13.79	13.31	13.04	12.97	13.07	14.79
090265	D	17.20	17.62	18.38	19.05	19.57	19.76	19.55	19.85	19.68	19.12	18.41	17.98
090465	N	24.22	23.78	23.35	22.80	22.52	22.28	22.02	21.12	20.92	20.83	20.89	21.61
090565	D	22.25	22.65	23.24	23.64	24.12	24.72	25.00	24.65	24.74	24.60	23.38	23.43
090865	N	23.71	23.00	22.30	21.76	21.30	20.86	20.53	20.32	20.13	20.05	20.07	20.83
090965	D	22.43	22.90	23.60	24.22	24.70	24.90	24.92	24.93	24.73	24.26	23.73	23.10
090965	N	22.27	21.69	21.44	21.12	20.70	20.04	19.72	19.29	19.03	19.25	19.25	20.31
091065	D	21.55	22.56	23.19	23.03	22.59	22.09	23.39	23.51	23.35	22.58	21.35	20.63
091365	N	21.60	21.13	20.95	20.33	20.44	20.68	20.58	20.85	20.61	20.38	20.10	20.68
091465	D	21.56	22.04	22.37	22.79	22.79	23.02	22.86	23.04	22.43	22.02	21.63	21.42
091465	N	21.76	22.46	22.21	21.05	20.50	20.48	20.35	20.34	20.40	20.23	19.91	20.19
091565	D	20.78	21.53	22.03	22.31	22.38	22.82	22.64	22.34	22.20	22.63	22.22	21.54
091565	N	21.22	21.34	20.90	20.53	20.53	20.58	20.44	20.15	19.84	19.75	19.90	20.46
091665	D	20.88	21.61	22.48	23.03	23.34	24.23	24.86	24.62	23.99	22.84	22.04	21.86
092265	N	15.12	14.89	14.95	14.63	14.55	14.28	13.69	13.47	12.75	12.43	12.86	13.07
092365	D	12.98	13.49	14.12	14.76	14.60	14.60	14.37	13.93	13.07	11.97	10.39	9.49
092365	N	9.33	8.93	8.56	8.43	8.39	8.26	8.11	8.29	8.19	8.00	8.36	8.38
092465	D	8.46	8.92	9.36	9.43	9.93	10.41	11.07	11.16	11.94	11.09	10.16	9.95
092465	N	9.70	10.50	10.72	10.65	10.50	10.63	10.63	10.80	10.75	10.75	10.75	10.46
092565	D	10.43	10.37	10.67	10.99	11.52	12.44	13.72	14.42	15.10	15.51	15.41	15.39
092565	N	15.47	15.35	15.28	15.40	15.08	14.60	14.26	13.96	13.83	13.61	13.42	13.89
092665	D	14.82	15.86	16.89	17.35	17.60	18.26	18.65	19.07	19.48	19.15	18.03	17.20
092665	N	16.55	16.09	15.70	15.43	15.37	15.13	14.93	14.52	14.05	13.56	13.40	13.98
092765	D	15.14	16.27	16.72	17.43	17.86	18.33	18.57	18.78	18.79	18.54	18.03	17.62
092765	N	16.91	16.29	15.90	15.35	14.91	14.61	14.30	14.24	13.87	13.43	13.15	13.77
092865	D	15.37	16.71	17.67	18.49	18.86	19.17	19.52	19.68	19.74	19.60	18.80	18.22
092865	N	17.92	17.54	17.39	16.95	16.82	17.00	16.92	16.57	16.16	15.68	15.54	16.03
092965	D	17.51	18.79	19.64	20.34	20.77	21.08	20.84	20.64	20.55	20.03	19.10	18.95
092965	N	19.01	18.72	18.52	17.49	12.11	10.60	10.21	9.98	9.14	8.49	8.06	8.14
093065	D	8.90	9.13	9.21	9.30	10.16	10.11	10.11	10.37	10.51	10.41	9.63	8.75
093065	N	8.55	8.40	7.78	7.37	7.25	6.99	7.13	7.12	6.79	6.10	6.34	7.89
100165	D	10.41	11.89	12.17	12.20	12.96	13.31	13.68	13.72	12.92	12.48	11.94	11.55
100165	N	10.06	9.51	9.14	9.10	8.37	7.17	7.78	7.76	7.13	6.58	7.02	8.43
100265	D	10.56	12.39	13.46	14.31	14.60	14.77	15.04	15.27	15.22	14.95	14.21	13.42
100265	N	13.00	12.41	11.90	11.83	11.08	10.54	10.46	10.43	10.47	8.76	8.66	9.87
100365	D	11.68	12.75	13.56	15.14	15.46	15.78	15.95	15.70	15.28	15.11	15.06	15.00
100365	N	14.81	14.52	14.41	14.09	13.74	13.42	13.20	13.29	13.05	12.86	12.96	13.19
100465	D	13.54	13.77	14.14	15.06	15.09	15.52	16.06	15.90	15.77	15.47	14.70	14.37
100465	N	13.88	13.46	13.01	12.42	12.09	11.58	10.64	11.01	11.27	11.20	11.44	12.44
100565	D	12.49	12.97	13.34	13.10	13.89	14.12	14.34	14.02	14.09	13.71	12.40	11.82
100565	N	11.63	11.90	11.62	11.37	11.09	10.61	10.08	10.14	9.97	9.87	9.80	10.62
100665	D	12.30	12.74	12.68	13.74	14.28	14.90	15.28	15.82	16.07	15.87	14.86	13.87
100665	N	13.50	12.95	12.44	12.34	11.77	11.78	11.86	11.78	11.87	12.00	11.91	12.81
100765	D	15.12	16.20	17.23	17.83	17.98	19.12	19.76	19.50	18.93	17.28	14.82	12.96
100765	N	12.26	11.81	11.84	10.79	9.84	10.21	9.55	9.50	9.26	9.07	8.81	10.22
100865	D	13.39	15.52	17.22	18.46	19.18	20.19	20.67	20.86	20.87	20.06	18.79	16.92
100865	N	15.90	14.72	13.86	13.42	13.16	12.46	12.09	12.33	11.84	11.92	10.83	12.35
100965	D	15.18	16.22	17.38	18.56	20.13	20.99	21.44	20.78	20.62	19.94	18.26	17.15
100965	N	15.75	15.28	14.52	13.82	13.14	12.94	11.77	10.87	11.58	11.26	10.96	11.66
101065	D	14.29	17.29	20.39	20.86	20.48	20.88	21.57	21.36	21.55	20.65	19.58	18.63
101165	N	8.06	7.30	6.90	6.40	5.97	5.27	5.06	4.51	3.97	3.55	3.46	4.96
101265	D	7.27	8.84	8.45	9.18	9.71	10.36	11.16	11.49	11.56	11.32	11.38	11.27
101265	N	11.35	11.49	11.88	11.96	11.91	11.61	11.07	10.71	10.96	10.91	10.55	10.88
101365	D	12.69	14.31	16.04	18.03	19.46	20.34	20.87	21.08	21.18	20.43	19.45	18.75
101365	N	17.83	17.00	16.77	16.69	16.59	16.78	17.02	17.10	17.05	16.92	16.92	17.39
101465	D	18.64	19.29	19.72	19.79	19.61	20.09	20.49	19.99	19.89	20.05	19.73	19.23
101465	N	18.70	18.46	18.30	18.27	18.19	18.28	18.23	17.23	17.32	16.61	17.09	17.11
101565	D	17.42	17.00	17.60	17.81	18.44	20.13	20.88	20.51	20.54	20.15	19.88	19.92
101565	N	19.68	19.33	19.36	19.40	19.31	19.29	19.13	19.27	19.50	19.51	19.50	19.50
101665	D	19.73	20.21	20.97	21.27	21.02	21.13	21.49	21.33	20.83	20.61	20.45	20.13
101665	N	20.28	20.36	19.95	19.43	19.10	18.89	18.62	18.41	18.30	18.00	17.81	17.68
101765	D	18.68	19.35	19.38	19.82	19.79	19.84	19.87	19.82	19.66	19.39	19.34	19.97
101865	N	16.16	16.18	16.19	16.18	16.25	16.36	16.34	16.07	15.92	15.71	15.04	14.99
101965	D	15.04	15.75	16.17	16.39	17.13	17.30	17.64	17.23	17.14	16.08	14.27	12.91
101965	N	12.41	11.79	11.02	10.44	10.16	9.83	9.35	8.84	8.37	7.99	8.05	9.07
102065	D	11.02	11.76	12.45	13.30	14.27	14.09	14.79	14.06	13.10	12.28	11.01	10.36
102065	N	9.82	9.64	9.41	9.12	8.79	8.54	7.98	7.30	6.73	6.28	5.88	6.30
102165	D	7.39	8.08	9.03	10.55	11.49	11.69	11.22	10.84	10.82	9.42	7.97	6.85
102165	N	6.35	5.68	5.36	5.05	4.99	4.50	3.46	3.22	2.78	2.10	1.86	3.50
102265	D	6.21	8.11	9.10	10.02	10.42	10.97	11.67	11.64	10.88	10.21	9.60	8.90
102265	N	8.31	7.45	7.15	7.37	7.87	8.32	8.32	7.98	7.78	8.52	8.67	9.18
102365	D	11.12	12.74	13.70	15.02	15.79	16.28	16.39	16.36	15.19	13.10	11.62	10.74

N REFERS TO NIGHT TIME HOURS; D REFERS TO DAYLIGHT HOURS

APPENDIX C

HOURLY WATER SURFACE TEMPERATURE OF TREATED POND

HOURLY WATER SURFACE TEMPERATURE OF UNTREATED POND

TABLE XXIII

HOURLY WATER SURFACE TEMPERATURE OF TREATED POND IN DEGREES CENTIGRADE

DATE	PER	HOUR INTERVAL											
		08-09	09-10	10-11	11-12	12-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
081365	N	26.71	26.49	26.24	26.08	25.94	25.80	25.57	25.47	25.26	25.17	25.08	25.09
081465	D	25.28	25.60	26.06	26.84	27.49	27.72	28.13	28.39	28.71	28.55	28.11	27.41
081465	N	27.37	27.13	26.99	26.88	26.84	26.66	26.56	26.41	26.34	26.21	26.19	26.22
081565	D	26.30	26.52	26.78	27.01	27.75	27.97	28.18	28.05	28.05	28.12	28.05	27.84
081565	N	27.49	27.30	27.09	26.97	26.80	26.71	26.65	26.50	26.33	26.30	26.23	26.25
081665	D	26.42	26.46	26.58	26.86	27.21	27.99	28.74	29.41	29.53	29.43	29.17	28.86
081665	N	28.62	28.37	28.14	27.91	27.75	27.58	27.43	27.30	27.12	26.95	26.90	26.95
081765	D	27.10	27.44	28.17	28.69	29.50	30.16	30.54	30.88	30.94	30.61	30.35	30.03
081765	N	29.77	29.54	29.25	29.08	28.94	28.72	28.50	28.34	28.14	28.01	27.90	27.99
081865	D	28.04	28.30	28.76	29.36	30.09	30.71	31.21	31.54	31.71	31.55	31.33	31.05
081865	N	30.94	30.78	30.67	30.52	30.35	30.14	29.96	29.84	29.76	29.52	29.33	29.20
081965	D	29.11	29.05	29.29	29.57	30.06	30.64	30.96	31.24	31.26	31.07	30.78	30.53
082065	N	30.08	29.77	29.56	29.48	29.39	29.23	29.00	28.85	28.80	28.64	28.61	28.64
082165	D	28.76	29.19	30.37	31.48	32.24	33.28	33.84	33.34	33.31	33.07	32.65	32.24
082365	N	32.58	32.08	31.73	31.41	31.12	30.83	30.70	30.44	30.32	30.15	30.04	29.93
082465	D	30.15	30.40	30.89	31.68	32.37	33.22	33.42	33.30	33.17	32.84	32.46	32.12
082465	N	31.89	31.72	31.48	31.18	30.99	30.79	30.47	30.26	30.04	29.92	29.74	29.60
082565	D	29.63	29.90	30.42	31.14	31.80	32.40	32.78	32.97	33.11	32.90	32.57	32.18
082565	N	31.87	31.60	31.32	31.01	30.62	30.29	29.94	29.65	29.36	29.06	28.82	28.70
082665	D	28.76	29.01	29.41	29.91	30.68	31.26	31.83	32.16	32.02	31.93	31.64	31.34
082665	N	31.02	30.73	30.48	30.24	29.97	29.73	29.50	29.22	29.05	28.77	28.53	28.50
082765	D	28.62	28.95	29.40	30.25	31.01	32.02	32.58	32.57	31.54	30.99	30.80	30.62
082765	N	30.51	30.35	30.13	29.98	29.83	29.63	29.50	29.38	29.10	28.96	28.82	28.74
082865	D	28.84	29.00	29.41	29.98	30.56	31.15	31.84	32.17	32.12	31.84	31.42	31.10
082865	N	30.74	30.46	30.28	29.97	29.89	29.66	29.43	29.30	29.07	28.83	28.69	28.68
082965	D	28.82	29.02	29.36	29.88	30.48	30.93	31.28	31.51	31.60	31.48	31.11	30.87
082965	N	30.58	30.30	30.08	29.88	29.57	29.31	29.05	28.86	28.65	28.46	28.29	28.16
083065	D	28.25	28.42	28.73	29.18	29.48	29.88	30.05	30.21	30.41	30.27	30.12	29.90
083165	N	26.39	26.06	25.91	25.60	25.51	25.20	25.00	24.94	24.77	24.57	24.42	24.38
090165	D	24.49	24.96	25.44	25.97	27.02	27.58	28.10	28.78	28.66	28.47	27.97	27.57
090165	N	27.14	26.75	26.45	26.24	26.04	25.84	25.77	25.65	25.54	25.29	25.04	24.91
090265	D	24.99	25.17	25.45	25.82	26.27	26.66	26.76	26.92	26.78	26.65	26.40	26.27
090865	N	31.16	30.92	30.58	30.26	29.98	29.74	29.49	29.30	29.15	28.99	28.79	28.74
090965	D	28.74	28.96	29.30	29.89	30.55	31.12	31.71	31.97	32.06	31.86	31.43	31.04
090965	N	30.71	30.32	30.13	29.85	29.76	29.63	29.52	29.39	29.22	28.95	28.83	28.74
091065	D	28.84	28.83	29.06	29.49	29.51	29.80	29.97	30.25	30.12	30.02	29.87	29.57
091365	N	29.06	28.91	28.78	28.78	28.68	28.53	28.44	28.14	27.94	27.66	27.46	27.47
091465	D	27.52	27.66	28.00	28.34	28.61	28.96	29.07	29.19	29.24	29.16	29.03	29.03
091465	N	29.03	28.86	28.77	28.46	28.20	27.98	27.76	27.56	27.46	27.29	27.02	26.90
091565	D	26.78	26.97	27.39	27.90	28.70	29.33	29.86	30.01	29.94	29.60	29.21	28.99
091565	N	28.71	28.35	27.97	27.71	27.44	27.28	27.04	26.80	26.61	26.51	26.32	26.19
091665	D	26.12	26.18	26.52	26.85	27.20	27.51	27.84	28.03	27.97	27.93	27.84	27.66
092365	N	21.32	21.05	20.80	20.60	20.41	20.21	20.05	19.90	19.79	19.59	19.49	19.47
092465	D	19.38	19.40	19.42	19.42	19.50	19.78	19.90	20.13	20.02	19.97	19.86	19.68
092465	N	19.60	19.60	19.54	19.47	19.46	19.41	19.38	19.33	19.16	19.08	18.95	18.98
092565	D	18.90	18.84	18.81	18.79	18.75	18.78	18.92	19.04	19.10	19.07	18.98	18.93
092565	N	18.90	18.90	18.85	18.74	18.64	18.60	18.51	18.41	18.40	18.31	18.11	18.22
092665	D	18.37	18.81	19.87	20.07	20.69	21.14	21.93	22.06	22.19	22.02	21.54	20.96
092665	N	20.55	20.21	19.95	19.63	19.45	19.40	19.32	19.17	19.00	18.86	18.79	18.78
092765	D	18.90	19.12	19.46	19.96	20.55	21.18	21.60	22.06	22.14	21.91	21.55	21.33
092765	N	21.08	20.92	20.68	20.50	20.39	20.18	20.08	19.95	19.90	19.80	19.60	19.57
092865	D	19.75	19.96	20.35	20.90	21.60	22.27	22.82	23.02	23.18	23.01	22.64	22.37
092865	N	22.05	21.89	21.68	21.46	21.35	21.23	21.10	21.02	20.83	20.75	20.61	20.60
092965	D	20.66	20.82	21.25	21.65	22.23	22.56	23.00	23.10	23.07	22.97	22.90	22.78
092965	N	22.62	22.55	22.41	22.36	22.07	21.78	21.51	21.29	20.98	20.68	20.36	20.09
093065	D	19.95	19.89	19.80	19.73	19.80	19.77	19.64	19.58	19.50	19.38	19.24	19.10
093065	N	18.99	18.92	18.78	18.67	18.56	18.48	18.44	18.36	18.20	18.06	17.90	17.88
100165	D	17.89	18.22	18.52	19.04	19.66	20.27	21.20	21.22	21.33	21.09	20.67	20.34
100165	N	20.01	19.74	19.51	19.43	19.25	19.16	19.05	18.91	18.79	18.60	18.52	18.49
100265	D	18.64	18.90	19.25	19.66	20.32	20.98	21.23	21.32	21.49	21.11	20.79	20.50
100265	N	20.29	20.00	19.84	19.78	19.67	19.52	19.49	19.40	19.34	19.20	19.10	19.07
100365	D	19.12	19.21	19.42	19.72	20.01	20.09	20.29	20.12	20.21	20.09	19.92	19.82
100365	N	19.70	19.61	19.60	19.56	19.50	19.50	19.46	19.40	19.41	19.38	19.29	19.11
100465	D	19.21	19.25	19.25	19.41	19.56	19.73	20.23	20.42	20.13	20.10	19.93	19.85
100465	N	19.77	19.58	19.51	19.50	19.40	19.40	19.27	19.18	19.10	19.10	19.02	19.05
100565	D	19.09	19.33	19.66	20.11	20.42	20.77	20.83	20.70	20.51	20.26	19.99	19.87

N REFERS TO NIGHT TIME HOURS; D REFERS TO DAYLIGHT HOURS

TABLE XXIV

HOURLY WATER SURFACE TEMPERATURE OF UNTREATED POND IN DEGREES CENTIGRADE

DATE	PER	HOUR INTERVAL											
		08-09	09-10	10-11	11-12	12-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
081365	N	26.01	25.82	25.52	25.32	25.26	25.10	24.96	24.84	24.63	24.60	24.48	24.50
081465	D	24.60	24.88	25.22	25.70	26.09	26.33	26.61	26.72	26.79	26.57	26.19	25.86
081465	N	25.71	25.60	25.52	25.32	25.14	25.09	25.02	24.91	24.87	24.73	24.66	24.81
081565	D	24.91	25.07	25.40	25.74	26.36	26.60	26.58	26.17	26.34	26.37	26.18	25.93
081565	N	25.73	25.56	25.38	25.18	25.04	24.95	24.86	24.70	24.53	24.51	24.48	24.50
081665	D	24.58	24.63	24.71	24.95	25.40	25.94	26.32	26.78	26.79	26.60	26.32	26.14
081665	N	25.98	25.82	25.63	25.48	25.37	25.28	25.06	25.04	24.91	24.84	24.80	24.74
081765	D	24.91	25.23	25.63	26.07	26.53	26.98	27.17	27.34	27.25	26.98	26.68	26.44
081765	N	26.21	26.07	26.00	25.89	25.75	25.49	25.24	25.10	24.90	24.80	24.66	24.73
081865	D	24.80	24.92	25.24	25.75	26.26	26.67	26.98	27.37	27.33	27.20	27.08	27.02
081865	N	26.93	26.76	26.74	26.67	26.59	26.43	26.36	26.29	26.21	26.12	26.00	25.92
081965	D	25.91	25.92	26.17	26.61	27.04	27.49	27.89	28.10	28.07	27.88	27.52	27.31
082065	N	27.08	26.91	26.78	26.49	26.40	26.30	26.24	26.06	25.93	25.86	25.70	25.70
082165	D	25.92	26.39	27.49	28.60	29.54	30.75	31.19	30.46	30.35	30.18	29.94	29.54
082365	N	30.29	29.79	29.33	28.91	28.47	28.12	27.76	27.46	27.29	27.12	26.91	26.87
082465	D	27.11	27.42	28.07	28.97	29.75	30.20	30.55	30.56	30.34	30.01	29.64	29.35
082465	N	29.03	28.70	28.21	28.02	27.85	27.68	27.47	27.34	27.18	26.95	26.76	26.62
082565	D	26.79	27.14	27.56	28.25	28.78	29.19	29.55	29.80	29.72	29.53	29.24	29.05
082565	N	28.79	28.47	28.23	27.94	27.66	27.52	27.22	26.95	26.83	26.57	26.37	26.31
082665	D	26.34	26.68	27.10	27.57	28.06	28.52	28.08	28.92	28.76	28.56	28.33	28.10
082665	N	27.87	27.62	27.52	27.28	27.10	26.81	26.64	26.47	26.33	26.12	25.93	26.02
082765	D	26.14	26.47	26.85	27.43	28.12	28.84	29.07	28.90	27.96	27.58	27.49	27.41
082765	N	27.34	27.22	27.19	27.06	26.87	26.68	26.55	26.41	26.29	26.11	25.91	25.87
082865	D	25.82	26.02	26.40	26.88	27.45	27.95	28.46	28.70	28.69	28.46	28.05	27.60
082865	N	27.37	27.15	26.92	26.73	26.57	26.42	26.27	26.03	25.90	25.81	25.61	25.61
082965	D	25.71	25.96	26.37	26.75	27.24	27.59	27.92	28.08	28.14	28.05	27.86	27.58
082965	N	27.45	27.36	27.17	26.91	26.74	26.57	26.30	26.10	25.86	25.67	25.49	25.45
083065	D	25.58	25.73	25.97	26.27	26.63	27.00	27.28	27.41	27.52	27.45	27.28	27.05
083165	N	24.22	24.08	23.74	23.51	23.22	22.91	22.79	22.61	22.51	22.32	22.20	22.15
090165	D	22.28	22.68	23.31	23.90	24.75	25.24	25.57	25.94	25.94	25.69	25.24	24.92
090165	N	24.60	24.31	24.04	23.89	23.73	23.58	23.42	23.32	23.15	22.95	22.64	22.59
090265	D	22.59	22.75	22.92	23.22	23.55	23.85	24.07	24.26	24.29	24.19	24.00	23.86
090465	N	26.57	26.41	26.16	25.55	25.78	25.59	25.36	25.21	25.13	25.01	24.78	24.69
090565	D	24.83	25.06	25.37	25.82	26.20	26.64	27.08	27.38	27.38	27.26	26.94	26.78
090865	N	27.99	27.86	27.62	27.47	27.35	27.18	26.77	26.60	26.55	26.38	26.37	26.22
090965	D	26.31	26.54	26.68	26.90	27.25	27.52	27.86	28.10	28.22	27.84	27.58	27.41
090965	N	27.34	27.14	27.08	26.97	26.70	26.56	26.44	26.39	26.26	25.98	25.80	26.18
091065	D	25.81	25.85	25.95	26.14	26.11	26.36	26.60	26.70	26.76	26.67	26.46	26.20
091365	N	25.77	25.64	25.52	25.40	25.39	25.15	25.10	25.10	25.08	24.78	24.54	24.49
091465	D	24.68	24.86	25.03	25.24	25.57	25.79	25.89	25.88	25.81	25.72	25.61	25.70
091465	N	25.67	25.58	25.63	25.47	25.25	25.11	25.04	24.87	24.63	24.37	24.26	24.10
091565	D	24.07	24.26	24.65	25.07	25.43	25.84	25.91	25.90	25.90	25.79	25.57	25.45
091565	N	25.22	25.08	24.88	24.61	24.40	24.15	23.94	23.83	23.63	23.48	23.40	23.25
091665	D	23.20	23.28	23.60	23.94	24.29	24.83	25.05	25.40	25.36	25.14	25.00	24.91
092265	N	22.91	22.51	22.27	22.32	21.92	21.73	21.62	21.51	21.36	21.15	21.04	20.91
092365	D	20.82	20.85	20.82	20.97	21.13	21.39	21.41	21.39	21.24	20.94	20.62	20.14
092365	N	19.95	19.54	19.20	18.94	18.81	18.67	18.52	18.41	18.25	18.11	18.01	17.90
092465	D	17.89	17.75	17.95	17.98	17.93	18.12	18.27	18.37	18.37	18.15	18.07	17.92
092465	N	17.90	17.90	17.87	17.86	17.69	17.60	17.55	17.51	17.43	17.43	17.41	17.37
092565	D	17.24	17.11	17.02	17.00	16.96	17.00	17.11	17.26	17.39	17.38	17.29	17.27
092565	N	17.22	17.13	17.10	17.07	16.99	16.90	16.87	16.77	16.75	16.65	16.51	16.57
092665	D	16.71	17.24	18.44	18.72	19.14	19.59	20.24	20.54	20.68	20.57	20.23	19.78
092665	N	19.45	19.03	18.66	18.41	18.19	18.09	17.97	17.90	17.74	17.60	17.50	17.49
092765	D	17.56	17.83	18.15	18.59	19.02	19.54	19.94	20.18	20.26	20.15	19.98	19.86
092765	N	19.63	19.52	19.34	19.17	19.05	18.90	18.87	18.71	18.68	18.56	18.45	18.38
092865	D	18.44	18.70	19.04	19.55	20.01	20.48	20.78	21.04	21.10	20.99	20.83	20.62
092865	N	20.48	20.29	20.15	20.05	19.92	19.88	19.75	19.58	19.50	19.40	19.35	19.28
092965	D	19.40	19.54	20.07	20.55	20.87	21.22	21.55	21.68	21.76	21.65	21.55	21.49
092965	N	21.41	21.28	21.09	21.07	20.86	20.55	20.20	19.86	19.56	19.27	18.91	18.64
093065	D	18.48	18.40	18.24	18.15	18.18	18.10	17.96	17.88	17.76	17.48	17.24	17.06
093065	N	16.94	16.90	16.75	16.58	16.48	16.38	16.20	16.13	16.06	16.00	15.95	15.81
100165	D	15.96	16.21	16.49	17.02	17.52	18.05	18.37	18.50	18.58	18.46	18.15	17.96
100165	N	17.76	17.54	17.46	17.25	17.10	17.00	16.89	16.81	16.64	16.50	16.40	16.40
100265	D	16.46	16.82	17.17	17.66	18.21	18.53	18.64	18.74	18.85	18.66	18.47	18.21
100265	N	18.08	17.96	17.78	17.79	17.89	17.53	17.44	17.31	17.18	17.10	17.10	17.10
100365	D	17.04	17.03	17.25	17.71	18.04	18.17	18.29	18.23	18.16	18.06	17.90	17.90
100365	N	17.74	17.60	17.60	17.60	17.56	17.53	17.50	17.46	17.37	17.39	17.37	17.34
100465	D	17.49	17.30	17.33	17.54	17.74	17.94	18.40	18.67	18.42	18.27	18.38	18.33
100465	N	18.03	17.93	17.88	17.65	17.60	17.48	17.42	17.40	17.28	17.19	17.24	17.23
100565	D	17.31	17.54	17.91	18.39	18.64	18.78	19.00	19.04	18.82	18.54	18.31	18.30
100565	N	18.09	17.91	17.84	17.64	17.53	17.26	17.10	17.09	16.91	16.85	16.95	16.66
100665	D	16.88	16.86	16.92	17.22	17.69	18.05	18.39	18.58	18.63	18.68	18.44	18.17
100665	N	17.98	17.87	17.64	17.57	17.46	17.65	17.30	17.11	17.06	16.94	16.89	16.89
100765	D	16.98	17.22	17.65	18.04	18.35	18.67	18.89	19.03	18.98	18.88	18.42	18.39
100765	N	18.18	18.05	17.98	17.87	17.69	17.60	17.42	17.31	17.22	17.09	17.00	16.98
100865	D	17.20	17.90	18.48	19.02	19.96	20.30	20.84	20.98	20.97	20.94	20.49	20.03
100865	N	19.67	19.35	19.06	19.01	18.61	18.46	18.35	18.20	18.11	17.95	17.85	17.74
100965	D	18.02	18.32	18.72	19.46	20.08	20.52	20.89	20.82	20.95	21.04	20.79	20.49
100965	N	20.21	19.96	19.69	19.49	19.38	19.25	19.10	18.98	18.83	18.72	18.58	18.54
101065	D	18.66	18.95	19.58	20.39	21.08	21.25	21.33	21.33	21.35	21.23	21.00	20.85
101165	N	17.14	17.00	16.98	16.67	16.50	16.32	16.20	16.08	15.98	15.77	15.83	15.67
101265	D	15.76	16.08	16.20	16.47	16.91	17.24	17.41	17.50	17.47	17.25	17.11	17.09
101265	N	17.01	17.06	16.92	16.85	16.80	16.69	16.61	16.57	16.66	16.30	16.20	16.20
101365	D	16.24	16.52	16.93	17.48	18.15	18.66	19.15	19.36	19.21	19.13	18.93	18.73
101365	N	18.52	18.44	18.24	18.11	17.94	17.87	17.83	17.90	17.79	17.77	17.70	17.81
101465	D	17.86	18.05	18.28	18.51	18.77	19.07	19.42	19.50	19.50	19.50	19.56	19.50
101465	N	19.59	19.58	19.50	19.38	19.09	19.07	19.01	18.84	18.71	18.62	18.76	18.63
101565	D	18.66	18.84	19.03	19.40	19.82	20.27	20.55	20.74	20.69	20.60	20.49	20.39
101565	N	20.23	20.19	20.19	20.05	19.95	19.85	19.83	19.79	19.80	19.81	19.71	19.75
101665	D	19.84	19.91	20.26	20.54	20.67	20.83	21.08	21.26	21.27	21.09	21.05	21.00
101665	N	20.91	20.79	20.67	20.66	20.54	20.49	20.39	20.39	20.38	20.12	20.06	19.92
101765	D	20.08	20.23	20.45	20.76	21.12	21.46	21.72	21.79	21.72	21.54	21.41	21.30
101865	N	19.00	18.89	18.90	18.86	18.94	19.04	18.88	18.72	18.65	18.56	18.50	18.51
101965	D	18.50	18.62	18.77	19.25	19.67	20.36	20.39	20.34	20.25	20.15	19.96	19.71
101965	N	19.43	19.32	19.11	18.96	18.76	18.56	18.46	18.36	18.11	18.07	17.95	17.60
102065	D	17.66	17.84	17.95	18.14	18.36	18.54	18.64	18.73	18.56	18.44	18.24	18.07
102065	N	18.18	17.70	17.52	17.28	17.25	17.08	16.48	16.28	16.05	15.80	15.69	15.54
102165	D	15.50	15.41	15.37	15.49	15.57	15.73	15.92	15.91	15.94	15.54	15.14	14.92
102165	N	14.79	14.43	14.18	14.06	13.88	13.78	13.64	13.54	13.37	13.04	13.02	12.86
102265	D	12.86	13.02	13.22	13.59	13.85	14.28	14.41	14.46	14.33	14.13	14.29	14.28
102265	N	13.98	13.84	13.72	13.72	13.71	[illegible]	13.57	13.56	13.41	13.33	13.19	13.18
102365	D	13.40	13.57	13.84	14.37	14.89	[illegible]	15.39	15.46	15.35	15.15	14.92	14.79

N REFERS TO NIGHT TIME HOURS; D REFERS TO DAYLIGHT HOURS

VITA

2

Harry Leo Manges

Candidate for the Degree of

Doctor of Philosophy

Thesis: HEAT AND MASS TRANSFER EQUATIONS FOR PREDICTING EVAPORATION REDUCTION BY MONOLAYERS

Major Field: Engineering

Biographical:

Personal Data: Born in Rice County, Kansas, June 18, 1928, the son of Elmer Fern and Charlotte Emily Manges.

Education: Graduated from Senior High School in Hutchinson, Kansas in 1945; graduated from Hutchinson Junior College in Hutchinson, Kansas in 1947; received the Batchelor of Science degree in Agricultural Engineering from Kansas State University in 1949; received the Master of Science degree in Agricultural Engineering from Kansas State University in 1959; completed the requirements for the Doctor of Philosophy degree from Oklahoma State University in August, 1969.

Professional Experience: Employed as an Agricultural Engineer by the Soil Conservation Service during 1949-1956, serving three years as an Area Engineer; employed as an Irrigation Research Engineer by Kansas State University during 1956-1964, assigned to the Irrigation Experiment Field in north central Kansas; employed as a Graduate Research Assistant by the Agricultural Engineering Department at Oklahoma State University during 1964-1966; employed as an Assistant Professor of Agricultural Engineering by Kansas State University during 1966-1969.

Professional Organizations: Member of the American Society of Agricultural Engineers; Registered Professional Engineer in the State of Kansas.