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Jumah Amayreh

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LAKE EVAPORATION: A MODEL STUDY

by

Jumah Amayreh

A dissertation submitted in partial fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Irrigation Engineering

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Lake Evaporation: A Model Study

by

Jumah Amayreh, Doctor of Philosophy
Utah State University, 1995

Major Professor: Dr. Robert W. Hill
Department: Biological and Irrigation Engineering

Reliable evaporation data are an essential requirement in any water and/or energy budget studies. This includes operation and management of both urban and agricultural water resources. Evaporation from large, open water surfaces such as lakes and reservoirs may influence many agricultural and irrigation decisions. In this study evaporation from Bear Lake in the states of Idaho and Utah was measured using advanced research instruments (Bowen Ratio and Eddy Correlation). Actual over-lake evaporation and weather data measurements were used to understand the mechanism of evaporation in the lake, determine lake-related parameters (such as roughness lengths, heat storage, net radiation, etc.), and examine and evaluate existing lake evaporation methods. This enabled the development of a modified and flexible model incorporating the tested methods for hourly and daily best estimates of lake evaporation using nearby simple land-based weather data and, if available, remotely sensed data.
Average evaporation from Bear Lake was about 2 mm/day during the summer season (March-October) of this two-year (1993-1994) study. This value reflects the large amount of energy consumed in heating the water body of the lake. Moreover, evaporation from the lake was not directly related to solar radiation. This observation was clear during nighttime when the evaporation continued with almost the same rate as daytime evaporation. This explains the vital role of heat storage in the lake as the main driving energy for evaporation during nighttime and daytime cloudy sky conditions.

When comparing over-lake and nearby land-based weather parameters, land-based wind speed was the only weather parameter that had a significant difference of about 50% lower than over-lake measurements. Other weather parameters were quite similar.

The study showed that evaporation from the lake can be accurately estimated using Penman-type equations if related parameters such as net radiation, heat storage, and aerodynamic effect are evaluated properly to reflect conditions over the lake. Using other methods may lead to unacceptable errors.

(190 pages)
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CHAPTER I
INTRODUCTION

Accurate estimation of evaporation from open water surfaces is a very important component of water resources planning and operation studies. Irrigation scheduling and development, design and operation of reservoirs, water balance studies, and water management are a few examples that require reliable evaporation data. Moreover, evaporation is one of the fundamental components of the hydrological cycle and should be considered in any computation of water and/or energy budgets.

Because evaporation plays a significant role in nature and influences many decisions that may affect human life, a reliable estimation of evaporation is a necessity for water resources management and, consequently, a part of agricultural and urban water development. As a result, reliable estimation and modeling of evaporation of lakes and reservoirs is desirable.

Problem Statement

The rate of evaporation from an open water surface is not easy to determine, due to the complexity of the nonlinear physical processes involved and despite the fact that it is a more simple system than land surfaces. In spite of this complexity, numerous methods have been developed to estimate the evaporation rates from various open water surfaces. These
methods can be classified under one of the following approaches:

- Water budget or mass budget.
- Bulk aerodynamic or mass transfer.
- Energy budget or heat budget.
- Pan conversion.
- Eddy correlation or eddy covariance.

Description of these methods will be given in the literature review chapter.

Selection of a suitable method to estimate evaporation is not an easy task, and usually depends on the availability and type of existing data. Unfortunately, estimation of evaporation using most of the existing methods will lead to different answers. In a study at two locations in Wyoming, Pathfinder Dam and Whalen Dam, reported by Waranka and Pochop (1988), a comparison of evaporation estimates was made using different equations. The equations varied greatly in their ability to estimate the magnitude and variability of evaporation. A similar result was obtained from the study of four Australian water storages reported by Hoy and Stephens (1977), in which three different evaporation methods were evaluated.

Moreover, the selection of any of the existing evaporation methods for any specific location does not mean that this equation is the best equation to model the evaporation in that specific location. This is because there
may be no accurate or trusted method of comparison. Under such circumstances, direct measurements of evaporation (if possible) remain the best approach and lead to better selection, calibration, and modeling of evaporation estimates. On the other hand, since type and availability of existing data are different from site to site, a flexible model that can deal with different types of data would be very practical and useful.

**Scope**

In this study, actual field measurements of the evaporation rates from Bear Lake in the states of Idaho and Utah were collected using advanced research methods and instruments (Bowen Ratio and Eddy Correlation). These measurements were used to examine and evaluate existing lake evaporation methods. Moreover, selected methods along with their parameters were calibrated to provide the best estimate of lake evaporation. Furthermore, a modified and more flexible model for lake evaporation was developed. The flexibility of the model derives from its ability to utilize the normally measured climatological data and by making use of remotely sensed data if available.

**Objectives**

The primary objective of this study was to analyze the factors affecting the evaporation rate from a large, free water surface with the goal of gaining a better understanding
of these factors and their actual effect on evaporation. These results were used to evaluate and calibrate existing lake evaporation methods, and to develop, using these adapted equations, a flexible model that uses nearby simple ground-based and, if available, remotely sensed data to best estimate evaporation from Bear Lake. The detailed objectives are as follows:

1. Collect reliable measurements of evaporation from Bear Lake along with meteorological data both over and near the lake in order to:
   - provide a better understanding of the mechanisms governing evaporation from the lake.
   - examine the utility and reliability of using nearby weather data as inputs for estimating lake evaporation.
   - improve modeling of the evaporation rate from free water surfaces.

2. Test and evaluate the ability of the existing evaporation methods in predicting the evaporation from Bear Lake using actual field measurements of evaporation and weather data. These methods include:
   - Bulk aerodynamic or mass transfer method in the form given by Lakshman (1972).
   - Wind function Penman-type method such as Kohler-Nordenson-Fox (1955) equation for evaporation from pans and lakes and modified Kohler-Nordenson-Fox
equation (Penman Lake equation) in the form given by Hill (1994).
- Aerodynamic resistance Penman type method in one of the forms given by Businger (1956), Van Bavel (1966), or Monteith (1965) if surface resistance \( r_c \) is equal to zero.
- Equilibrium evaporation method in the form given by Priestley and Taylor (1972).
- Pan conversion method.

3. Calibrate these methods, if applicable, to best estimate lake evaporation in hourly and daily basis aiming to investigate and predict lake evaporation for both day­light and night times.

4. Develop a lake evaporation model, utilizing the above mentioned adapted equations, that will permit the estimation of evaporation rates using nearby simple ground-based and, if available, remotely sensed data.

5. Perform a sensitivity analysis of the proposed model that will clarify the variations of the estimates due to errors in the input data.
CHAPTER II
LITERATURE REVIEW

In the literature many studies have been reported for estimating evaporation rates from free, open water surfaces and lakes. In fact, many of these methods are based directly upon the famous equation derived by Penman (1948) for modeling open water surface evaporation. In this chapter a brief description of the existing evaporation methods reported in the literature will be presented. Also, applications of remote sensing techniques related to evaporation will be discussed.

Water Budget

In this approach the principle of conservation of mass is assumed, in which the supplies to the lake must equal the sum of losses and changes in lake storage. Although this method is the most simple and direct method in its concept, in practice it is very difficult to perform accurate measurements of all the flow terms in the water budget equation, especially the interaction between surface and groundwater. So, its applicability and accuracy is questionable in most of the cases. This method has been used in evaporation estimates at Lake Hefner (Maniciano and Harbeck, 1954) Lake Michie (Turner, 1966), Salton Sea (Sturrock, 1987), and many others.
Bulk Aerodynamic

The basic concept of this approach is the removal of water vapor from an open water surface due to turbulent diffusion, which is considered to be related to wind speed and vapor pressure difference between saturation vapor pressure at the water surface and the ambient air vapor pressure at some height above the water surface. Publication of the Dalton equation in 1802 is considered the first attempt to express this concept in a mathematical form as (Calder, 1990):

\[ E = (e_{so} - e_a) F(u) \]  \hspace{1cm} (1)

in which \( E \) is the evaporation rate; \( e_{so} \) is saturation vapor pressure corresponding to the water surface temperature; \( e_a \) is vapor pressure of the ambient air; and \( F(u) \) is some unknown function of wind speed \( u \).

Since the time of Dalton to date, many researchers have suggested various forms of the wind function \( F(u) \). Numerous different empirical forms have been reported, mostly linearly related to wind speed raised to a power equal to or less than unity as (Penman, 1948; Kohler et al., 1955; Harbeck, 1962; Kohler and Parmele, 1967):

\[ F(u) = a + b u^n \]  \hspace{1cm} (2)

in which \( a, b, \) and \( n \) are empirical coefficients. In general,
these are empirical expressions that suffer from the fact that turbulence is only vaguely proportional to wind speed. One of the widely used forms of the wind function is a linear one in which the aerodynamic formula has the following shape (Harbeck, 1962; Turner, 1966; Hughes, 1967; Quinn, 1979):

\[ E = N u (e_{so} - e_a) \]  

(3)

where, \( N \) is called the aerodynamic coefficient or the mass transfer coefficient. The value of \( N \) depends on several factors such as units used in the equation, wind speed measurement height, lake size, atmospheric pressure, and climatic conditions and stability (Harbeck, 1962). One of the major problems using aerodynamic formula is determining the value of \( N \). However, many researchers have tried to find the value of \( N \) using various levels of empiricism (Harbeck, 1962; Lakshman, 1972; Brutsaert, 1982).

As a result of detailed study from Lake Hefner and Lake Mead in which the coefficient \( N \) was obtained from energy budget and evaporation-seepage studies, Harbeck (1962) introduced a formula to determine \( N \) which related to lake size as:

\[ N = \frac{0.00859}{A^{0.05}} \]  

(4)

where \( A \) is the water surface area in acres. \( N \) as given in Eq.
(4) corresponds to wind speed in miles per hour, vapor pressure in mb, and estimated lake evaporation in inches per day. Lakshman (1972) has derived a formula for determining $N$ in terms of lake shape and turbulent boundary parameters as:

$$E = N u_2^{0.8} (e_{so} - e_a)$$

where

$$N = \frac{(3.9E-4) m^{0.2}}{(m+1)^{1.6}} \frac{\delta^{1.8m}}{(2m+1)^{0.2}} \frac{P}{A}$$

and $u_2$ is the wind speed at 2 m height in miles per hour; $m$ is the exponent of a power-type wind law having the form of $u_z = az^m$ in which $u_z$ is the wind speed measured at height $z$ from water surface, $a$ and $m$ are constants; $\delta$ is the turbulent boundary layer thickness in meters (Lakshman, 1972); $A$ and $P$ are the area in square feet and perimeter in feet of a water body, respectively; and $e_{so}$ and $e_a$ are in mb.

Energy Budget

The concept of energy or heat budget to estimate evaporation was credited to Schmidt in 1915 when he computed evaporation from oceans (Anderson, 1954). However, at that time Schmidt faced many difficulties in estimating or measuring some of the terms in the energy budget, such as incident and reflected solar radiation, incident and reflected atmospheric radiation, longwave radiation from the water body,
and energy stored in the water body. Since 1915 many investigators have successfully used the energy budget approach to estimate evaporation from different water bodies and lakes making use of the continuous progress in both understanding and estimation of different energy budget terms.

The simplified energy budget equation for any surface can be written as:

\[ R_n - G = LE + H \]  

(7)

in which \( R_n \) is the net longwave and shortwave radiation flux; \( G \) is the heat flux into the surface; and \( LE \) and \( H \) are the latent heat flux and the sensible heat flux from the surface, respectively. The sum of sensible and latent heat fluxes must equal the sum of values of the net radiation \( R_n \) and the flow of heat into the surface \( G \). The net radiation \( R_n \) can be measured or estimated (Burman et al., 1983; Hill et al., 1983; Allen, 1986; Kustas et al., 1989; Jensen et al., 1990). The water heat flux \( G \) is not easy to measure due to the convection problem in water. However, investigators usually neglect it by choosing a suitable energy budget interval in which they assume no change in heat storage of entire water volume during that interval. Bowen (1926) overcome the difficulty of estimating the sensible heat flux to or from the water body by introducing what was known later as the Bowen Ratio (BR), which represents the ratio of the sensible heat flux to the
latent heat flux. Using this ratio, the evaporation can be estimated using the Bowen Ratio energy equation as:

\[ \text{LE} = \frac{R_n - G}{1 + BR} \]  

Moreover, with the assumption of the equality of heat and vapor diffusion coefficients and the assumption that \( H \) and \( LE \) are proportional to mean gradients of both temperature and vapor pressure, Bowen (1926) developed a theoretical expression of the Bowen Ratio in terms of easily measured quantities:

\[ BR = \gamma \frac{T_s - T_a}{e_s - e_a} \]  

where

\[ \gamma = \frac{C_p P}{L \varepsilon} \]  

in which \( \gamma \) is the psychometric constant; \( T_s \) is water surface temperature; \( T_a \) is air temperature; \( e_s \) is saturation vapor pressure at water surface temperature; \( e_a \) is vapor pressure at air temperature; \( C_p \) is specific heat of air at constant pressure; \( P \) is the barometric pressure; \( L \) is latent heat of vaporization; and \( \varepsilon \) is the ratio of the molecular weights of the water vapor and air. Because sources of heat and water
vapor are not the same and because of the difficulty of measuring surface properties, the following equation is normally used:

\[
BR = \gamma \frac{T_{z2} - T_{z1}}{e_{z2} - e_{z1}}
\]  

(11)

where derivatives have been estimated by finite differences. In the above equation the subscripts z1 and z2 refer to the two level of measurements at z1 and z2, respectively.

The Bowen Ratio technique gives an accurate estimation of evaporation if the temperature and humidity gradients, net radiation, and heat flux terms can be measured accurately. However, determination of the Bowen Ratio requires accurate measurements of surface temperature, which is not an easy aspect in most cases. Penman (1948) tried to overcome the problem by proposing a technique in which he eliminated the requirement for the need to measure surface temperature. In doing so, Penman (1948) used the Clausius-Clayperon equation to define the slope of the saturation water vapor pressure-temperature calculated at mean air temperature, taking only the first term of Taylor series expansion. The final form of the famous Penman energy equation, also known as the Penman combination equation, is:
\[ LE = \frac{A}{A + \gamma} (R_n - G) + \frac{\gamma}{A + \gamma} K_u E_a \]  \hspace{1cm} (12)

\[ E_a = F(u) (e_s - e_d) \]  \hspace{1cm} (13)

where \( A \) is the slope of the saturation vapor pressure-temperature curve; \( K_u \) is a units conversion constant, \( (R_n - G) \) is expressed in equivalent evaporated water; and \( e_s \) is the saturation vapor pressure corresponding to ambient air temperature \( T_a \). Here \( e_d \) is taken as the saturation vapor pressure at dew point temperature or actual vapor pressure of air.

Although the Penman combination equation has been widely used and considered one of the most reliable evaporation equations worldwide for almost half a century, it still has been the subject of numerous theoretical and experimental studies, and to date there is no common accepted way to formulate the wind function \( F(u) \) (Brutsaert, 1982). The original wind function to appear in the Penman (1948) equation was:

\[ F(u) = 0.26 (1 + 0.01 u_2) \]  \hspace{1cm} (14)

where \( u_2 \) is the wind speed at two meter height in km/day. However, eight years later Penman (1956) proposed an improved wind function as:
\[ F(u) = 0.26 (0.5 + 0.01 u) \]  

(15)

However, Penman (1963) recommended again the original wind function as in the 1948 Penman equation.

In an attempt to use the Penman combination equation to approximate pan evaporation, Kohler (1954) adjusted the psychometric constant to account for the sensible heat conducted through the sides and bottom of the pan based on the Lake Hefner studies. The psychometric constant was found to be 0.025 inches of mercury per degree F for the elevation of Lake Hefner. In 1955 Kohler, Nordenson, and Fox reevaluated the aerodynamic portion of the Penman combination equation using pan data from four locations scattered across the United States. Their study resulted in the following expression (Kohler et al., 1955):

\[ E_a = (0.37 + 0.0041 u_p) (e_s - e_d)^{0.88} \]  

(16)

in which \( u_p \) is wind speed six inches above the rim of a class A pan in miles per day; \( e_s \) is saturation vapor pressure at air temperature in mb; and \( e_d \) is saturation vapor pressure at dew point temperature in mb. However, the above procedure is questionable since boundary layer properties, and scales and properties of turbulence are completely different over pans compared to lakes. Assuming lake evaporation is 70%, of a
class A pan, this resulted in a modified evaporation equation as (Kohler et al., 1955):

\[ E_1 = \frac{0.7}{L} \left[ \frac{\Delta}{\Delta + \gamma_1} R_n + \frac{\gamma_1}{\Delta + \gamma_1} (0.37 + 0.0041 u_p) (e_s - e_d)^{0.88} \right] \]  

(17)

and

\[ \gamma_1 = 0.000367 P \]  

(18)

where \( E_1 \) is the average daily lake evaporation in inches; \( L \) is the latent heat of vaporization; \( \gamma_1 \) is lake psychometric constant in inches of mercury per degree F; \( \Delta \) is the slope of vapor pressure-temperature curve (same units as \( \gamma_1 \)); \( P \) is the atmospheric pressure in inches of mercury; and other parameters are as previously defined.

Hill (1994) adapted the Penman combination equation (Eq. 12) and the Kohler-Nordenson-Fox equation (Eq. 17) for estimating evaporation from lakes. By assuming the albedo and emissivity of water surface equal to 0.06 and 0.97, respectively, by neglecting the heat flux into the lake (assuming \( G = 0 \)), and by adjusting the wind function of Eq. (12) to reflect that of Eq. (17), Hill (1994) introduced Penman-Lake equation as:
\[ E_1 = \frac{0.7}{L} \left[ \frac{\Delta}{\Delta + \gamma} R_{nl} + \frac{\gamma}{\Delta + \gamma} \right] 15.36 \left(1 + 0.01 u_2 \right) (e_s - e_d) \]  \hspace{1cm} (19)

and

\[ R_{nl} = 0.94 R_s - 0.97 R_b \]  \hspace{1cm} (20)

where \( R_{nl} \) is the estimated net radiation over the lake; \( R_s \) is the incoming solar radiation; \( R_b \) is the net outgoing longwave radiation; and other parameters are as defined earlier. However, assuming \( G = 0 \) in Eq. (19) is not a valid assumption in some situations of high latitude lakes where heat flux is significant.

Van Bavel (1966) used a modified function based upon a formula derived originally by Thornthwaite and Holzmann (1939), in which the modified wind function assuming log-law for neutral atmosphere appeared as:

\[ F(u) = \frac{\epsilon \rho K^2}{P \left[ \ln \frac{Z}{Z_0} \right]^2} u_z \]  \hspace{1cm} (21)

in which \( \rho \) is density of air; \( Z_0 \) is roughness parameter; \( u_z \) is wind speed at height \( z \); \( K \) is the Von Karman constant (nearly equal to 0.41); and other parameters are as defined earlier.
A similar relation was derived earlier by Businger (1956).

Monteith (1965) modified the original Penman combination equation to be used for crops by incorporating aerodynamic resistance \( (r_a) \) and bulk stomatal resistance \( (r_c) \) terms into the empirical aerodynamic portion of the equation. By doing so, Monteith tried to include surface resistance. Despite the fact these resistance terms are not easy to be measured or estimated, the turbulence effect was better incorporated. The general form of the Penman-Monteith equation is:

\[
LE = \frac{\Delta}{\Delta + \gamma^*} (R_n - G) + \frac{\rho C_p}{\Delta + \gamma^*} \frac{1}{r_a} (e_s - e_d)
\]  (22)

where

\[
\gamma^* = \gamma (1 + \frac{r_c}{r_a})
\]  (23)

and

\[
r_a = \frac{\ln \left( \frac{z}{z_{om}} \right)}{\frac{\ln \left( \frac{z}{z_{oh}} \right)}{K^2 u_z}}
\]  (24)

in which \( z_{om} \) is the roughness length for momentum transfer; \( z_{oh} \) is the roughness length for heat transfer; \( \rho \) is the air density; and other parameters are as defined earlier. The bulk stomatal resistance term \( (r_c) \) is considered equal to zero in the case of open water surfaces (Kaimal and Finnigan, 1994).
The above aerodynamic equation is valid for about 30-minute time averages assuming neutral atmosphere logarithmic wind profile, and assuming measurements are made in the lower few meters of the atmosphere. The first part of the combination equation is known as the energy or radiation term \( (\text{LE}_{\text{rad}}) \), while the second part is known as the aerodynamic term \( (\text{LE}_{\text{aero}}) \).

Many modifications trying to adapt the Penman equation for different situations were reported in the literature. One of these modifications is a study presented by Priestley and Taylor (1972) in which they modeled the evaporation in the case of no advection for a poorly coupled system. In other words, this case represents minimal turbulent exchange of mass and heat between the surface and atmosphere (decoupled system). Under such conditions the energy part of the Penman equation dictates the evaporation rate and the equation reduces to the following:

\[
E_{eq} = \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (25)
\]

where \( E_{eq} \) is the equilibrium evaporation. Moreover, by examining data from ocean, lakes, and saturated surfaces where advection exists, but is hopefully minimal, Priestley and Taylor (1972) introduced the parameter \( \alpha \) into the above equilibrium equation as an empirical constant to account for
energy advection as:

\[ E = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \]  \hspace{1cm} (26)

By using eight data sets tested by the authors, a value of 1.26 was found to be the best value of \( \alpha \) for evaporation from uniformly saturated surfaces under a minimal advection condition (Priestley and Taylor, 1972). Later Stewart and Rouse (1977) verified the Priestley and Taylor model using data from two shallow lakes in northern Canada. Their conclusion was to assign the same numerical value of 1.26 to the empirical constant \( \alpha \) in high latitudes.

A different form of the energy budget approach was developed by Morton (1979) to estimate evaporation from lakes and reservoirs on a monthly basis. The method included an energy weighting factor \( \psi \), and an advected energy term \( M \) combined with net radiation \( R_n \), assuming the water surface temperature is at air temperature (which is not a good assumption for many lakes such as Bear Lake). Lake evaporation \( E_w \) is thus given by:

\[ E_w = \psi \left( R_n + M \right) \]  \hspace{1cm} (27)

with \( \psi \) and \( M \) defined as (Morton, 1979):
\[ \psi = 0.26 + \left[ 1 + \frac{r}{\Delta} \left( \frac{0.5 + 0.5r + \frac{r}{\Delta}}{r + \frac{r}{\Delta}} \right) \right]^{-1} \] (28)

\[ M = 0.66 R_b - 0.44 R_w \quad \text{where } M \geq 0 \] (29)

where \( r \) is the relative humidity as a ratio (0 to 1); \( \tau \) is the heat transfer coefficient in \( \text{mb/}^\circ\text{C} \); \( R_b \) is the net longwave radiation loss if the surface were at air temperature in \( \text{Wm}^{-2} \); and other parameters are as previously defined.

The above equations are the basis for estimating net radiation and lake evaporation from any observation of air temperature, dew point temperature, and sunshine duration that are made in the vicinity of the lake. According to Morton (1979), the complexity of the model is due to the use of sunshine duration to estimate the radiation components and to a generality that permits it to be used in any part of the world.

**Net Radiation**

Accurate estimation of net radiation is the key in any energy balance studies in general, and Penman-type equations in particular. Net radiation is considered the driving energy for the other three components of the simplified energy budget equation (Eq. 7) for any surface, namely heat flux into the surface (G), latent heat flux (LE), and sensible heat flux (H).
Net radiation is the algebraic sum of net shortwave and net longwave radiation. Net shortwave radiation is the difference between incident and reflected shortwave radiation, while net longwave radiation is the difference between incoming and outgoing longwave radiation. Incident shortwave radiation represents the radiation emitted from the sun with wave length equal to or less than 3 μm. This includes direct sunshine, and radiation scattered or reflected by the atmospheric particles or clouds. A portion of incident shortwave radiation is reflected upward upon reaching the surface, and the ratio of reflected to incident shortwave radiation is called the surface albedo ($a_s$). Albedo is a function of surface type, incident angle, and atmospheric conditions. Average daily albedo values of 0.04 to 0.08 are commonly used for water surface (Brutsaert, 1982).

Longwave radiation represents radiation emitted from earth objects with wave lengths greater than 3μm. So, net longwave radiation is the difference between the amount of longwave emitted downward from atmospheric constituents, including water vapor, carbon dioxide, and other absorbing gases and clouds, and that emitted upward from the object surface. The longwave radiation can be estimated using the well-known Stefan-Boltzmann law as:

$$LW = \varepsilon \sigma T^4$$

(30)
where $\epsilon$ is the emissivity; $\sigma$ is the Stefan-Boltzmann constant; and $T$ is the absolute temperature in Kelvin. The well-known net radiation equation has the following form (Kustas et al., 1989):

$$ R_n = (1-\alpha_s)R_s + \epsilon_{atm}\sigma T_a^4 - \epsilon_{surf}\sigma T_s^4 $$

(31)

The above equation requires both "effective" emissivity of the atmosphere ($\epsilon_{atm}$) and emissivity of the surface ($\epsilon_{surf}$) to be known. Additionally, surface albedo $\alpha_s$, solar radiation $R_s$, "effective" atmospheric temperature $T_a$, and surface temperature $T_s$ should be known. A commonly used value for emissivity of water is 0.97 (Brutsaert, 1982). Both "effective" atmosphere temperature and emissivity are difficult to measure or estimate since temperature and atmospheric particle concentrations vary greatly with height (Kaufman, 1989). Many researchers have tried to estimate the atmospheric emissivity; however, the resulting empirical forms are mostly for clear sky situations. Two of these proved to give quite accurate estimations of atmospheric emissivity during this study. The first is an equation given by Brutsaert (1975) as:
\[ \varepsilon_{atm} = 1.24 \left( \frac{10 \, e_d}{T_a} \right)^{\frac{1}{7}} \]  

(32)

and the second is an equation given by Idso (1981) as:

\[ \varepsilon_{atm} = 0.7 + \frac{59.5}{10^5} \, e_d \exp\left( \frac{1500}{T_a} \right) \]  

(33)

where \( T_a \) is temperature in Kelvin at screen height and \( e_d \) is vapor pressure in kpa at screen height. The 0.7 constant is site specific depending on dustiness of the air (Jensen et al., 1990). In case of cloudiness these emissivity equations may be adjusted by introducing a cloud correction factor.

Another difficulty of using the net radiation equation is the requirement of availability of surface temperature measurements. Practically, surface temperature measurement availability is very limited. Many empirical equations were reported in the literature to estimate net longwave radiation. These equations use air temperature instead of surface temperature. One of the widely used empirical equations, a form proposed originally by Penman (1948) and modified by Doorenbos and Pruitt (1977), has the following form:
\[ R_n = (1 - \alpha_s) R_s - \sigma T_s^4 \left( 0.34 - 0.044 \sqrt{e_d} \right) \left( 0.1 + 0.9 \frac{n}{N} \right) \] (34)

where \( n \) is the actual hours of sunshine, and \( N \) is the possible hours of sunshine. The last expression of Eq. (34) is an empirical cloudiness correction. A further modification was presented by Wright (1982) in which he used daily maximum and minimum air temperatures instead of average temperature for 24-hour time steps. Also, in his equation he substituted the cloudiness correction term of Eq. (34) by another comparable form originally developed by Wright and Jensen (1972). This modified equation has the following form (Wright, 1982):

\[ R_n = (1 - \alpha_s) R_s - \sigma \left( \frac{T_x^4 + T_N^4}{2} \right) \left( a_1 + b_1 \sqrt{e_d} \right) \left( \frac{R_s}{R_{so}} + b \right) \] (35)

where \( T_x \) is the maximum air temperature; \( T_N \) is the minimum air temperature; \( R_{so} \) is the clear sky solar radiation; and \( a_1, a, b_1, \) and \( b \) are empirical coefficients calibrated by Wright's (1982) for Kimberly, Idaho. Values of Wright's (1982) empirical coefficients are shown in Appendix C (Table C1).

In a review of the literature, several researchers have developed a simple linear regression model to estimate net radiation. Most of these models predict net radiation from solar radiation measurements with high correlation
coefficients. Although this procedure of estimating net radiation is useful during daytime hours, it cannot be used during nighttime periods.

**Lake Heat Storage**

Estimation of lake evaporation using the energy budget method requires a prior knowledge of change in heat storage in the lake. A survey of water temperature profile is the common procedure to estimate the change in heat storage in lakes. Although this procedure is considered the most accurate method to estimate the change in heat stored in lakes, it is very costly and time and labor consuming. Moreover, the accuracy of this method decreases rapidly for short periods. In the Lake Hefner, Oklahoma studies, Anderson (1954) showed that with all the components measured with great care and when the measurements periods were a week or longer, accuracy of evaporation estimates approached ±5%. In another study, the accuracy of evaporation estimates was determined to approach ±10% at Lake Mead, Nevada for biweekly measurement periods (Koberg, 1958).

Many investigators tried to evaluate the impact of using fewer measurement sites in the accuracy of lake heat storage estimation. Rosenberry et al. (1993) reported only a 2% deviation from evaporation best estimates, when using one location rather than 16 locations to estimate lake heat storage, from William Lake (maximum depth is 9.8 m),
Minnesota. Similar results were concluded during the Lake Hefner (average depth is about 10 m) studies (Anderson, 1954; Crow and Hottman, 1973).

Water Surface Roughness Lengths

One of the very important parameters when using Penman-type equations is aerodynamic resistance for heat and water vapor transport. As mentioned earlier, aerodynamic resistance $r_a$ can be estimated using an equation for neutral condition (Eq. 24), or using the more general form of the $r_a$ equation by considering stability correction terms. However, for either case, values of both roughness length of momentum, $z_{om}$, and roughness length of heat or vapor, $z_{oh}$ or $z_{ov}$ assuming they are equal, must be determined. The accurate numerical values of these roughness parameters are difficult to determine. However, for homogeneous, uniform, and rough surfaces, the roughness length of momentum, $z_{om}$, may be calculated utilizing the logarithmic wind function under neutral conditions or from direct measurement of friction velocity ($u_*$). There is no known way to measure the other roughness parameters, such as roughness length of heat, $z_{oh}$, and roughness length of vapor, $z_{ov}$.

Roughness parameters have been the subject of numerous theoretical and experimental investigations. The difficulty rises from the fact that in nature so many factors may affect the values of these roughness parameters. For example, some
investigators believe that roughness length of momentum, $z_{om}$, is a function of atmospheric stability (Sutton, 1953). Others reported that over some surfaces, roughness length of momentum, $z_{om}$ increases with increasing wind speed while over other surfaces it decreases with increasing wind speed (Priestley, 1959; Monteith, 1973; Monteith and Unsworth, 1990). Based on many lab experiments, investigators showed the importance of distinguishing between smooth and rough surfaces, particularly in the aerodynamic sense. In this concern, they introduced what is called the roughness Reynolds number ($z_o^+$) as (Brutsaert, 1982; Garratt, 1992):

$$z_o^+ = \frac{u_* z_o}{v} \quad (36)$$

where $z_o^+$ is a dimensionless roughness Reynolds number; $u_*$ is friction velocity in ms$^{-1}$; and $v$ is flow viscosity in m$^2$s$^{-1}$. Friction velocity, $u_*$, also known as shear velocity, is a fluids characteristic that has the dimension of velocity. $u_*$ is a function of surface roughness length and under atmospheric neutral conditions is given by:

$$u_* = cd_z^{0.5} u_z = \frac{u_z K}{\ln\left(\frac{z}{z_{om}}\right)} \quad (37)$$
where $c_d_z$ is a dimensionless empirical drag coefficient referred to wind speed at height $z$ ($u_z$). Over extensive water surfaces such as oceans, drag coefficient usually is related to wind speed at 10 m height. Most of the existing empirical expressions linearly relate drag coefficient, $c_{d_{10}}$, to wind speed at 10 m, $u_{10}$, as (Kondo and Fujinawa, 1972; Smith, 1974; Brutsaert, 1982; Garratt, 1992):

$$c_{d_{10}} = (A + B u_{10}) \times 10^{-3} \quad (38)$$

where $A$ and $B$ are empirical constants. Experiments over water showed that values of $c_{d_{10}}$ were ranging from $0.7 \times 10^{-4}$ to $2.2 \times 10^{-3}$ with a typical average of $1.4 \times 10^{-3}$ (Kondo and Fujinawa, 1972; Smith, 1974; Wieringa, 1974; Brutsaert, 1982; Garratt, 1992).

The roughness Reynolds number, $z_o^+$, is used to distinguish between smooth and rough surfaces. A smooth surface has a $z_o^+ < 0.13$, while a rough surface has a $z_o^+ > 2$. A surface of $0.13 < z_o^+ < 2$ has mixed properties of smooth and rough surfaces (Brutsaert, 1982; Garratt, 1992). Based on this definition, very few surfaces are considered to be smooth surfaces in nature. Water, snow, ice, fine sand, and salt flats are some examples of smooth surfaces; however, under high wind speeds these surfaces may behave as rough surfaces. Water surface has been reported to behave as a smooth surface with wind speeds
of 5 ms\(^{-1}\) (Priestley, 1959). Experiments showed that with smooth surface conditions roughness length of momentum, \(z_{om}\), is smaller than either roughness length of heat, \(z_{oh}\), or roughness length of vapor, \(z_{ov}\). Theoretical values of roughness length of momentum, \(z_{om}\), were given as (Plate, 1971; Brutsaert, 1982; Garratt, 1992):

\[
\frac{z_{om}}{u_*} = 0.135 \frac{v}{u_*} \quad \text{for } z_0^+ < 0.13 \quad (39)
\]

and

\[
\frac{z_{om}}{g} = 0.016 \frac{u_*^2}{g} \quad \text{for } z_0^+ > 2 \quad (40)
\]

Both Plate (1971) and Garratt (1992) estimated the coefficient in Eq. (39) to be 0.11 rather than 0.135 given by Brutsaert (1982). Also, the ratio of \(z_{om}\) to \(z_{oh}\) was estimated to be about 1 to 3 and 1 to 2 according to Brutsaert (1982) and Garratt (1992), respectively. Brutsaert (1982) reported that in some laboratory channel experiments with a super-smooth surface the observed \(z_{om}\) was less than the expected theoretical value previously mentioned. Many investigators tried to explain this phenomenon. For example, Casanady (1974) believed this was due to surface tension effect. Kondo and Fujinawa (1972) related this to atmospheric stability neglection. Plate (1971) explained the above phenomenon as due to wind which induces a current in the direction of the wind
profile, relative to which the logarithmic wind profile is valid. So, the surface appears smoother than a smooth solid surface. Values in the range of 0.01 to 1 mm have been reported in the literature for roughness length of momentum zom for open water (Priestley, 1959; Plate, 1971; Brutsaert, 1982; Arya, 1988; Garratt, 1992).

Atmospheric Stability Adjustment

A neutral atmosphere is rarely observed. Stable or unstable conditions are most likely to dominate the atmospheric stability. So, the influence of stability should be considered whenever applicable, especially in hourly or shorter time-step calculations. The theory of Monin and Obukhov in 1954 is considered the most accepted atmospheric stability theory world wide. The Monin-Obukhov length is a measure of atmospheric stability condition given by:

\[ l = \frac{\rho c_p u_*^3 T_v}{g K H} \]  

(41)

in which \( l \) is the Monin-Obukhov length in meters; \( u_* \) is friction velocity in \( \text{ms}^{-1} \); \( T_v \) is virtual temperature in Kelvin; and other variables are as previously defined. The Monin-Obukhov length corresponds to the height at which the values of mechanical and thermal production of turbulence are equal. Determination of the Monin-Obukhov length is not simple, since it requires the value of sensible heat \( H \) and \( u_* \) to be known,
which is not the case most of the time. So, this leads to a nonlinear set of equations, which requires iterative kinds of solutions. However, a more simple measure of atmospheric stability is the bulk Richardson number, which is approximated as:

$$R_i = \frac{z g}{T_z} \frac{\theta_s - \theta_z}{u_z^2}$$

(42)

where $R_i$ is Richardson number (dimensionless); $g$ is the acceleration of gravity $\text{ms}^{-2}$; $u_z$ and $T_z$ are the wind speed in $\text{ms}^{-1}$ and air temperature in Kelvin at height $z$, respectively; and $\theta_s$ and $\theta_z$ are the surface and the air potential temperatures, respectively. The general form of aerodynamic resistance that takes the stability correction into consideration is given by:

$$I_a = \frac{[\ln(\frac{Z}{Z_{cm}}) - \Psi_m] [\ln(\frac{Z}{Z_{coh}}) - \Psi_h]}{K^2 u_z}$$

(43)

in which $\Psi_m$ and $\Psi_h$ are integral stability functions of atmospheric correction for momentum and heat, respectively. Usually these stability functions are a function of either Monion-Obukhov length or Richardson number. Numerous empirical and analytical solutions have been reported to evaluate these correction functions (Viney, 1991; Choudhury et al., 1986; Byun, 1990; Mahrt and Ek, 1984; Webb, 1970; Dyer, 1974; Hicks
et al., 1977). A comparison of some of these stability correction functions related to the aerodynamic resistance term given by equation (43) is presented by Kalma (1989).

Evaporation Pan Conversion

This technique is very well known worldwide since it is the simplest and cheapest method to estimate evaporation from lakes. The idea behind this method is to measure the amount of water evaporated from a standard pan and then correlate it to lake evaporation. The correlation coefficient is known as the pan coefficient \( C_{ep} \), which relates pan evaporation \( E_p \) to lake evaporation \( E_l \) as:

\[
E_l = C_{ep} \ E_p
\]  

There are many different types of evaporation pans with different size and shapes; however, the class A pan is the most popular one in the U.S. and many other countries as well. Pan coefficients vary widely depending on pan type. It may also vary from site to site, season to season, and lake to lake for the same pan type. A mean annual value of a class A pan coefficient is about 0.7, which was suggested by many researchers based on results from many countries (Hounam, 1973). According to Kohler et al. (1955), the 0.7 coefficient has been recommended since 1932 by the American Society of Civil Engineers (ASCE) and became a customary practice. However, numerous values of class A pan coefficients were
reported, ranging from 0.13 to 2.53 based on monthly data (Hounam, 1973). These variations are due to the big difference between pans and lakes in their heat storage characteristics as a result of size variations and pan wall side effects. To ensure a good representation of lake evaporation, a floating pan is much better than a pan on land. However, experience on floating pans leads to the conclusion that data are unreliable because of continuous splashing of water in and out of the floating pan (Hounam, 1973). A good review of evaporation from pans and pan coefficients is presented by Hounam (1973), Kohler et al. (1955), and Webb (1966).

Eddy Correlation

The eddy correlation method may be considered the only direct method to measure evaporation. The main idea of the eddy correlation method is to measure the turbulent transport of water vapor in the vertical direction. The major problem associated with the eddy correlation method is the requirement of very fast response instruments to measure the water vapor and the vertical wind speed fluctuations at high frequencies to capture the small size, high frequency eddies created near the evaporating surface. However, in the few last years new fast response sensors and data loggers have been developed that are capable of measuring and storing these type data with sufficient speed and accuracy. Using Reynolds averaging rules, the latent heat flux can be expressed as (Stull, 1988):
where \( \rho \) is the air density; \( w' \) is the deviation of vertical velocity from the mean vertical velocity \((w)\); and \( q' \) is the deviation of specific humidity from the mean specific humidity \((q)\). The same concept can be shown for turbulent heat transport, where the sensible heat flux can be expressed as \((\text{Stull, 1988})\):

\[
H = \rho \ C_p \ T'_a \ w'
\]  

where \( T'_a \) is the deviation of air temperature from the mean air temperature \( T_a \); and other parameters are as previously defined.

**Remote Sensing**

Although remote sensing is relatively a new technology, its applications are expanding rapidly. A well known technique estimates evaporation rates as a residual of the energy balance using both remotely sensed and ground-based measurements in evaluating other energy balance terms \((\text{Kustas et al., 1989})\). Reflected shortwave radiation can be measured using remote sensing applications, and remotely sensed surface temperature can be used to estimate longwave radiation emitted from the surface. Along with other variables and assumptions, the sensible heat flux can be estimated. Later, these values,
in conjunction with the other ground-based measurements, can be used to estimate evaporation as a residual.

A few attempts to relate lake evaporation to water surface temperature have been made in which thermal infrared satellite data were used as for Utah Lake (Woodruff and Rango, 1985), Great Salt Lake (Woodruff and Millis, 1989), and Lake Okeechobee (Xin and Shin, 1991). However, such studies have two main problems. First, the remotely sensed surface temperature may still have an error of 15 to 20%, which is associated with satellite altitudes even if atmospheric correction is taken into account (Kiang, 1982). Second, in all the above mentioned studies, water surface temperature was correlated to evaporation from pans, which does not reflect the actual evaporation from the lakes as mentioned earlier. Also, satellite flights may be only once per day and not continuous.
Site Description

Bear Lake (42.07N, 115.15W) is a high altitude lake about 1800 m above mean sea level. The lake is located in the states of Idaho and Utah, with a surface area of about 282 km$^2$, and perimeter of about 80 km (see Fig. 1). The lake varies greatly in depth, with maximum depth of about 60 m near the mid eastern shore and average depth of about 30 m. In general, the lake has a mild bottom slope near the western shore, and quite steep slopes near the eastern shore. The lake usually freezes in winter (January-March), and reaches an average surface temperature of about 20$^\circ$C in mid summer.

Procedures

In this section the procedures followed to reach each objective (see Chapter I) will be stated. Later in the following sections instrumentation used will be described.

Objectives 1 & 2:

a- Meteorological measurements were collected using two land based electronic weather stations located near Bear Lake as shown in Fig. 1. These were at the Lifton pumping plant and at the Utah State University (USU) limnology research laboratory south of Garden City.
FIGURE 1. Bear Lake Site and Experiment Measurements Locations.
b- Actual evaporation estimates from Bear Lake were made using both the Bowen Ratio and Eddy Correlation methods. Besides the normal measurements taken by these instruments over the lake, weather data and temperature profile of water were measured.

c- Using Eddy Correlation instrument, both latent heat (LE) and sensible heat (H) fluxes were measured.

d- Using the measured $R_n$, LE, and $H$, heat flux in the water surface, $G$, was estimated by residual and compared to $G$ from temperature profile measurements.

e- $G$ was also modeled using simple factors in order to be used with Bowen Ratio and Penman-type methods.

f- Using the above measurements, existing lake evaporation methods were examined and evaluated.

Objective 3:

a- By making use of the continuous evaporation and weather data measurements mentioned above, selected lake evaporation methods were calibrated for best estimates of evaporation rates for use with nearby land-based weather data. This will enhance historical and future lake evaporation estimates using these calibrated methods.

b- Since measurements were made continuously during the day and night, diurnal trends in evaporation from the lake are presented and analyzed.
Objective 4:

a- By flying over the lake and sensing emitted thermal infrared radiation from the water surface, the water surface temperature was estimated and examined for any spatial temperature variation.

b- A flexible model was developed, utilizing the above mentioned adapted methods, which uses simple nearby ground-based and, if available, remotely sensed measurements.

c- With the remotely sensed surface temperature a better estimation of lake evaporation was reached from a better estimation of net radiation and incorporation of the atmospheric stability effect on evaporation.

Objective 5:

A sensitivity analysis was performed which led to an evaluation of the variations in estimated lake evaporation due to input data accuracy.

Land-Based Measurements

Meteorological data were obtained from two nearby land-based electronic weather stations as shown in Fig. 1. The first station was located near the mid western shore at the USU limnology research laboratory south of Garden City, Utah. The second station was located on the northern shore at the Lifton pumping station, Idaho. Air temperature, soil temperature, relative humidity, wind speed at 3 m height, wind direction, and solar radiation were sampled every 60 sec at
both stations using Campbell Scientific Inc. (CSI)\(^1\) CR-10 data loggers. These measurements were recorded every 60 minutes as average, maximum, and minimum values. Data were available from both stations during summer 1993. However, for summer 1994, data were available from the Lifton station only.

**Over-Lake Measurements**

Over-lake measurements were collected during summers of 1993 and 1994. These included both evaporation and climatological data measurements. In this section the instrumentation used and their setup will be clarified.

**Evaporation measurements**

In this study, two sets of instruments (Bowen Ratio and Eddy Correlation) were used to estimate the actual evaporation from the lake. Both instruments were installed side by side over the water near the northern shore of the lake (see Fig. 1). Each instrument was mounted on a separate tripod over the water where the depth varied from 70 to 100 cm. The distance from the shore varied from 150 to 200 m.

**Bowen Ratio system.** The Bowen Ratio measurements were made continuously from August 17 to October 23, 1993, and from March 3 to October 27, 1994. The Bowen Ratio, BR, system is a Campbell Scientific Bowen Ratio system which uses a Dew-10

\(^1\) Use of brand or commercial names in this study is for identification purposes only and does not constitute or imply a recommendation of endorsement.
General Eastern Chilled mirror hygrometer to measure the dew point temperature, with a resolution of ±0.003°C. Air temperature was measured by a 76 μm copper-constantan thermocouple with resolution of ±0.006°C. Dew point temperature and air temperature were scanned every two seconds from two measurement levels above the water surface (1.25 and 2.25 m where the water depth was 1 m).

**Net radiation and heat flux to the lake.** Accurate measurements of net radiation, $R_n$, and heat flux to the lake, $G_l$, are essential factors for estimation of latent heat flux (evaporation) using BR energy balance method, or any other energy-based methods.

In this study, net radiation was measured by a REBS Q6 net radiometer. In summer 1993, the Q6 net radiometer was checked with another Q6 net radiometer for about a week. The two radiometers gave almost identical measurements. However, as a result of the summer 1993 data analysis and due to the uncertainty of this important term, $R_n$, especially at nighttime, a cross calibration with a brand new Swissteco net radiometer was made during summer of 1994 from September 15 to October 2. Net radiation measurements were scanned every 60 seconds.

Attempts to estimate heat flux to the lake in summer 1993 were done by measuring the temperature profile using two sets of 11 thermocouples (9 in water and 2 in bottom sand), and two soil heat flux plates inserted at about 2 cm depth into the
bottom sand. The thermocouples in each set were 10 cm vertically spaced with the first thermocouple kept 5 cm under the water surface. The two sets were about 8 m apart.

In addition to the water temperature profile thermocouples, three floating thermocouples were used to estimate the water surface temperature. In summer 1994 and as a result of analyzing the 1993 summer data, the measurements were reduced to one set of two thermocouples at two depths of about 15 and 45 cm from water surface, with two floating thermocouples to measure the water surface temperature. All thermocouple sensors and soil heat flux plates were scanned every 10 seconds.

The BR system was driven by a Campbell Scientific 21X data logger, while the 22 thermocouples along with soil heat flux plates were differentially connected to another 21X data logger using a Campbell Scientific AM416 Relay Multiplexer. All BR system measurements were recorded as averages into 20-minute intervals, and as hourly and daily average, minimum and maximum values. Maintenance for BR system was performed every 10 to 14 days. This included cleaning and balancing the Dew-10 mirror. The domes of the REBS Q6 net radiometer were cleaned at the time of maintenance and, sometimes, more frequently as required.

**Eddy Correlation system.** An Eddy Correlation (EC) system was used in this study to get independent measurements of latent heat and sensible heat fluxes. The system consisted of
a Campbell Scientific CA-27 one-dimensional sonic anemometer equipped with a 13 μm chromal-constantan fine wire thermocouple and a Campbell Scientific KH-20 Krypton hygrometer. The system was mounted about 2 m over the water surface with transverse distance of 8 to 10 cm between the sonic and krypton center axes. A Campbell Scientific 21X data logger was used to monitor the measurements of vertical wind speed, fluctuation in air temperature relative to the temperature of the sonic base, and air humidity.

The monitoring frequency was 10 HZ. A 10-minute averaging period was used to calculate means, covariances, and other intermediate computations. The final output interval was 20 minutes to match the BR system timing. The output included the averages of latent and sensible heat fluxes during the 20-minute interval. Later, collected data were corrected to account for oxygen absorption and density variation effects (using a correction program provided by Dr. Lawrence E. Hipps, Plants, Soils, and Biometeorology Department, USU). Moreover, collected data were screened for good fetch (wind direction relative to orientation of sonic and krypton) where data were rejected when prevailing winds were blowing from a 90° arc (northwest to northeast). By using the Eddy Correlation system, 400 hours worth of data were collected in summer 1993 during the period August 31 to September 23. In summer 1994, the Eddy Correlation system was used continuously during three separate periods: a) June 15
to June 23, b) July 15 to July 30, and c) August 1 to August 8, which represents 35 days worth of data.

Besides the benefits of having independent measurements of latent and sensible heat fluxes, this large amount of data along with net radiation data was used to estimate the heat flux to the lake by residual. As it will be explained in the next chapters, this procedure enabled the modeling of heat flux to the lake \( (G_t) \) using more simple parameters.

Maintenance of the EC system was performed daily. This included checking the leveling of the sonic anemometer and cleaning the windows of the Krypton hygrometer by wiping them with a wet cotton swab. Daily cleaning of the Krypton windows was necessary to overcome the problem of signal attenuation due to the buildup of an unknown deposit on the Krypton hygrometer windows. The deposit seems to be caused by some kind of reaction of the air with the Krypton radiation, and can be easily removed by wiping the windows with damp cotton (Campbell Scientific, personal communication, 1993).

Climatological Data

Besides the measurements of evaporation and other energy balance factors over the lake, over-lake measurements of climatological data including those required as input parameters for Penman-type equations were also collected.

In summer 1993, duplicate sets of weather sensors included air temperature, relative humidity, wind speed and direction, and solar radiation. The first set of sensors was
connected to the Bowen Ratio 21X data logger. All sensors in this set were brand new sensors. First set sensors included:

- HMP35C (Vasila) probe mounted at about 2 m above water surface for measurements of temperature and humidity of the air.
- RM Young Wind Monitor mounted at about 3.5 m above water surface for measurements of wind speed and direction.
- LI-COR LI200S silicon pyranometer mounted at about 2.5 m above water surface for measurement of solar radiation (direct and diffuse shortwaves).

The second set of sensors was redundant for the purpose of double check only. All the sensors in this set were either brand new or newly calibrated. This set of sensors was connected to the 21X data logger, which was monitoring the water temperature profile thermocouples. Second set sensors were:

- Campbell Scientific 107 thermistor probe mounted at about 2 m above water surface for air temperature measurements.
- Campbell Scientific 201 thermistor and RH probe mounted at about 2 m for measurements of air temperature and humidity.
- Met-One 014 three-cup anemometer and Met-One 024A Wind Direction sensors mounted at about 3 m above water surface for measurements of wind speed and wind direction, respectively.
- LI-COR LI200S silicon pyranometer mounted at about 2.5 m above water surface for solar radiation measurement.
Only the first set of sensors, associated with the BR system, was used in summer 1994. All air temperature and relative humidity sensors were shielded from direct sunshine by mounting into a multi-plate radiation shield.

**Miscellaneous Data**

Besides the above mentioned measurements, the following miscellaneous data were either measured directly by the writer, or measured and provided by other agencies or researchers.

**Albedo Measurements**

Water surface albedo measurements were taken during summer 1994 on July 31 and August 7. The measurements were made through the deployment of an Exotech 4 band radiometer. The radiometer has four Thematic Mapper bands, TM1 (0.45-0.52 μm), TM2 (0.52-0.60 μm), TM3 (0.63-0.69 μm), and TM4 (0.76-0.90 μm), and can measure the reflected shortwave radiation including both direct and diffuse components of solar radiation. The measurements were taken near the mid western shore to get measurements in shallow water as well as deep water.

A barium sulfate reflectance panel was used to estimate the bi-directional reflectance in each spectral band. Measurements were taken through the day starting at 9:30 AM and up to about 7:30 PM local time with readings taken about every 2 hours. A Polycorder 700 was used to record all the
measurements. Measurements reflect both shallow and deep water. Moreover, measurements on July 31 represent a partly cloudy and quite windy day, while measurements on August 7 represent a mostly sunny and calm day. Assuming a partial to total (P/T) reflected radiation of 0.55, albedo was calculated as the ratio of reflected to incident radiation. In this study, the water albedo estimates made with the 4-band radiometer used a P/T value of 0.55, which was originally determined from data over green crop (Jackson, 1984). However, since the resulted over-water albedo estimates agreed well with the cited literature values, the assumption of over-water P/T ratio of 0.55 seemed to be reasonable.

**Water Temperature Profile**

A water temperature profile in the deepest point in the lake was provided from the USU College of Natural Resources, Dr. Chris Luecke records. The data were taken manually using a mercury thermistor attached to a long rope. The measurements covered the entire depth (about 60 m) with a variable depth step increment of 1 to 5 m. The frequency of measurements was about once per month in summer 1993, and once every 3 weeks in summer 1994.

**Land-Based Class A Pan Evaporation**

The evaporation from a class A evaporation pan was available from National Climatic Data Center (NCDC) monthly reports. The pan was land-based, located at the Lifton pumping
station on the northern shore. The observations were made daily during summer months.

Survey of Water Surface Temperature

Water surface temperature all over the lake was remotely sensed and surveyed on September 11, 1993. The purpose of the survey was to check any spatial variations of surface temperature in the lake which may affect the energy balance components all over the lake.
During the summers of 1993 and 1994 a large amount of over-lake weather and energy balance data was collected. Having double sets of sensors for some time periods measuring climatological conditions gave reliability in the quality of collected data. The strong correlation among different sets of weather data is evidence of the accuracy of collected measurements. The bias in the collected weather data measurements seems to be within the expected normal errors associated with the accuracy of the sensors used.

Concerning the energy balance data, as it will be shown in this chapter, every component of the energy balance was checked either theoretically or by a different type of measurement approach. Again the energy balance measurement comparison supported the previously drawn conclusion that the accuracy of the collected measurements was within the normal manufactured accuracy of the instrumentation used. The above discussion shows that the collected data are satisfactory from both quantity and quality points of concern. In this chapter, results drawn from this 2-year research study will be discussed and analyzed.

Analysis of data collected during the summers of 1993 and 1994 is presented in this chapter. However, since a large
amount of analyzed data had similar results, only representative sample results will be presented and discussed.

**Net Radiation over the Lake**

As mentioned previously, net radiation is considered the most important factor in the simplified energy budget equation (Eq. 7). Therefore, strict attention was used while measuring this term. In the summer of 1993, besides the direct measurements of net radiation using the Q6 net radiometer, the water surface temperatures were measured using floating thermocouples. The remotely sensed (from aircraft flight) surface temperature on September 11, 1993 compared well with the floating thermocouple measurements. Also, the remotely sensed surface temperature measurements showed no significant spatial variations of water surface temperature over the lake (see Appendix A). This agrees with the uniform temperature profiles horizontally and vertically as reported during Lake Hefner studies (Anderson, 1954).

The measurements of water surface temperature enabled the estimation of outgoing longwave radiation. This allowed the estimation of net radiation using the well-known net radiation equation (Eq. 31). The 1993 summer data analysis showed that while \( R_n \) measurements compared well with the estimated \( R_n \) from the net radiation equation (Eq. 31 with hourly \( \alpha_s \) given by Eq. 47 and \( \epsilon_{atm} \) given by Eq. 49) during the daytime, considerable variation was detected during the nighttime. Therefore, in
the summer of 1994, a Swissteco net radiometer (Net Pyrradiometer # 8240, Type S-1) was used during a 2-week experiment. The Swissteco net radiometer was mounted beside the Q6 net radiometer. The objective of this experiment was to get another independent measurement of net radiation in order to recalibrate the Q6 net radiometer if necessary. The experiment results showed strong agreement between Swissteco and Q6 net radiometer measurements during the daytime with maximum deviation of 2% as shown in Fig. 2.

During the nighttime, the Swissteco agreed with the estimated $R_n$ from Eq. (31), but it was about 42% negatively greater than the Q6 measurements as shown in Fig. 3. In fact, the strong agreement between the $R_n$ measurements by Swissteco and estimated $R_n$ from Eq. (31), led to readjustment of all the measurements of Q6 during the nighttime.

**Water Albedo**

To estimate the net shortwave radiation, the albedo of water should be determined. The measurements of the albedo on July 31, 1994 and August 7, 1994 showed how the albedo of water varied during early mornings and late afternoons, while it was quite constant during most of the day. For hourly calculations, the albedo of water can be related to the zenith angle of the sun since both albedo and zenith angle have similar trends as shown in Fig. 4.
FIGURE 2. Daytime Hourly Net Radiation Comparison Over Water.

FIGURE 4. Water Albedo Measured and Estimated Using Eq. (47) and Sun Zenith Angle Versus Time.
Based on the estimates using a 4-band radiometer, the average value of 0.055 was estimated as a suitable value for the water albedo in daily calculations. For hourly calculations, an empirical relation was found which relates water albedo with the sun zenith angle. This empirical equation is:

\[ \alpha_s = 0.045 + 0.12e^{-0.08(90-\theta)} \]  

(47)

where \( \theta \) is the zenith angle of the sun in degrees.

This empirical equation was based on 2 day’s worth of data and did not take other factors, such as cloudiness, wind, and wave conditions in the lake, into consideration. However, this equation is useful for hourly calculations since the albedo of water is almost constant during most of the day, varying a few hours after sunrise and before sunset when incoming solar radiation is minimal.

Emissivity of the Atmosphere

Atmospheric emissivity equations of both Brutsaert (1975) and Idso (1981) were tested in this study. Both models compared well under clear sky conditions. However, there were slight variations under cloudy sky conditions. Based on measurements of \( R_n \) during cloudless sky situations, Eq. (31) was inverted to calculate the emissivity of the atmosphere as:
The dustiness constant in the Idso (1981) model was estimated to be 0.64 for Bear Lake conditions. In this study the Idso (1981) equation of atmospheric emissivity was used to estimate incoming atmospheric longwave radiation as:

\[
\varepsilon_{atm} = \frac{1}{\sigma T_a^4} \left[ R_n - (1 - \alpha_s) R_s + \varepsilon_{surf} \sigma T_s^4 \right]
\]  

(48)

A comparison between atmospheric emissivities calculated by residual from Eq. (48) and estimated from Eq. (49) is presented in Appendix C (Fig. C1).

Estimation of Net Radiation

Although net radiation was measured during this study, for future estimations of lake evaporation this term could be estimated. In this concern, two cases were analyzed—case 1: when surface temperature measurement is available; and case 2: when surface temperature measurement is not available.

Case 1: when surface temperature is available. When water surface temperature is available, the well-known net radiation equation (Eq. 31) is recommended. In this study, albedo of water was taken equal to 0.055 for daily calculations, and
from Eq. (47) for hourly calculations. Emissivity of the atmosphere was taken as Eq. (49). Air and water surface temperatures were either hourly or daily averaged in Kelvin degrees.

For both hourly and daily calculations, strong agreement of $R_n$ was verified between Eq. (31) and actual measurements during clear sky conditions. However, during cloudy sky conditions, it was necessary to correct the net longwave term. The comparison between measured and estimated net radiation for both clear and cloudy skies is shown in Fig. 5. A simple correction factor based on the ratio of actual incoming shortwave radiation $R_s$ to clear sky radiation $R_{so}$ worked very well. The corrected net radiation equation along with the cloudiness correction factor (CC) was taken as follows:

$$R_n = (1 - \alpha_s)R_s + CC \left[\varepsilon_{atm}\sigma T_s^4 - \varepsilon_s\sigma T_a^4\right]$$

(50)

where

$$CC = 0.35 \frac{R_s}{R_{so}} + 0.65 \text{  if } \frac{R_s}{R_{so}} \geq 0.7$$

or

$$CC = 0.65 \frac{R_s}{R_{so}} + 0.35 \text{  if } \frac{R_s}{R_{so}} < 0.7$$

(51)
FIGURE 5. Hourly Net Radiation Comparison Over Water.
Case 2: when surface temperature is not available. Since water surface temperature is not available in most situations, it is important to estimate net radiation using air temperature instead of surface temperature. A procedure shown by Wright (1982), Eq. (35), was selected to estimate net radiation over the lake. However, by using the same empirical coefficients given by Wright (1982) for Kimberly, Idaho, a considerable error was found both in daily and hourly time step calculations. This result led to adjustment and calibration of these coefficients to fit the measurements taking into account the cloudiness correction (as given by Eq. 51), if required. The new calibration coefficients are:

For hourly data:

\[ a_1 = 0.385 + 0.1 e^{-(0.0154(JD-180))^2} \quad \text{for } JD<150 \text{ or } JD>235 \]

or

\[ a_1 = 0.26 + 0.1 e^{-(0.0154(JD-180))^2} \quad \text{for } 150<JD<235 \]

and

\[ b_1 = -0.12 \quad \text{(52)} \]

For daily data:

\[ a_1 = 0.38 + 0.1 e^{-(0.0154(JD-180))^2} \quad \text{for } JD<150 \text{ or } JD>235 \]

or
\[ a_1 = 0.30 + 0.1 \ e^{-(0.0154(JD-180))^2} \ for \ 150 < JD < 235 \]

and
\[ b_1 = -0.12 \] \hspace{1cm} (53)

where JD is day of the year (1 to 366). The comparison of measured and estimated net radiation using Wright (1982) coefficients (see Appendix C, Table C1) and the new coefficients (Eqs. 52-53) is shown in Fig. 6. Even though these new coefficients were based on more than 7 months worth of data, they may be location specific for Bear Lake to estimate net radiation over open water.

The net radiation over the lake is considerably higher than the expected net radiation over land by about 20% during daytime. However, during nighttime \( R_n \) over the lake is lower (more negative) than over land \( R_n \) by about the same percentage (20%). Daily comparison of measured and estimated net radiation using the above mentioned two cases (Eq. 50 and Eq. 35) is shown in Fig. 7.

**Heat Flux to the Lake**

Intensive analysis was done to estimate the heat flux to the lake as accurately as possible, since it is a very important term for BR energy calculations as well as for any energy-based equation to estimate evaporation. The first step was the attempt to estimate \( G_i \) by summing the change in heat storage in the water (from water temperature profile
FIGURE 7. Daily Comparison of Measured and Estimated Net Radiation Over Water. $R_n(\text{NEW CAL})$ is Eq. (35) Using Parameters from Eqs. (52-53) and CC from Eq. (51), $R_n(T_s)$ is Eq. (50) Using $\epsilon_{\text{atm}}$ from Eq. (49) and CC from Eq. (51).
measurements) and the heat flux into the bottom sand (from soil heat flux plate measurements). The heat flux into the bottom sand was very small, varying from -15 Wm\(^{-2}\) to +10 Wm\(^{-2}\). This procedure of analysis was tested for 20 minutes and 60 minute measurement intervals. The calculation expressions were as follows:

\[
G_1 = \Delta st + G_p
\]  

(54)

where

\[
\Delta st = \frac{C_w}{(\Delta t)} \sum \Delta T \Delta Z
\]  

(55)

where \(G_1\) is the heat flux to the lake in Wm\(^{-2}\); \(G_p\) is the measured heat flux to the bottom sand in Wm\(^{-2}\); \(\Delta st\) is the rate of change in heat storage of water in Wm\(^{-2}\); \(\Delta t\) is the time step interval in sec; \(C_w\) is the specific heat for water which equals 4180 j kg\(^{-1}\) C\(^{-1}\); \(\Delta T\) is the change in water temperature over the time step interval \(\Delta t\); \(\Delta Z\) is thickness of sublayer (100 mm in this study); and \(n\) is the number of sublayers.

Although the measurements of the two sets of temperature profile thermocouples and the measurements of the two soil heat flux plates agreed very well, the estimated \(G_1\) using the above procedure was inconsistent. The running average of \(G_1\) provided better results, but not enough to apply the BR energy procedure. The inconsistency was obvious by examining the closure (the ratio of "\(Rn - G\)" to "\(LE + H\)"), which varied
randomly. For example, while the closure was about 1.0 in some cases, it varied from 0.1 to 2 for other cases even though longer time steps (daily up to weekly) were tested. The convection problem in water (especially during nighttime where warm water in the shallow shore have been substituted by colder water from deep layers) was believed to be the main reason for that inconsistency. A sample of the comparison results between $G_1$ estimated from Eqs. (54-55) and calculated by residual from energy balance (Eq. 56) is presented in Appendix C (Fig. C2). This obvious inconsistency led to search other procedures to estimate $G_1$.

The above unexpected results in estimating $G_1$ suggested using a different method. Large data from the Eddy Correlation and net radiation measurements were most helpful in evaluating other approaches. The heat flux to the lake $G_1$ was estimated by residuals as:

$$G_1 = R_n - LE - H$$  \hspace{1cm} (56)

In fact, for future estimates of $G_1$ it is necessary to predict $G_1$ using other factors which can be measured or estimated easily. A statistical and stepwise regression procedure was used to relate residual $G_1$ with the most significant factors. The factors entered in the analysis were air temperature, surface temperature, bottom sand temperature,
air relative humidity, wind speed, and net radiation. Average, minimum, and maximum values of these factors were entered in the analysis (see Table C2 in Appendix C for some of the statistical output results). The statistical procedure gave the following prediction equations:

For hourly data:

During daytime \((R_n>0)\):

\[
G_{lp} = -68.5 + 0.998 R_n \quad (R^2=0.98) \tag{57}
\]

During nighttime \((R_n<0)\):

\[
G_{lp} = 7.82 + 1.2 R_n - 22.56 u_2 \quad (R^2=0.89) \tag{58}
\]

For daily data:

\[
G_{lp} = -62 + 0.984 R_n \quad (R^2=0.92) \tag{59}
\]

where \(G_{lp}\) is the Predicted heat flux to the lake in Wm\(^{-2}\); \(u_2\) is the wind speed at 2 m in ms\(^{-1}\); and \(R^2\) is the coefficient of determination. As shown above, it is obvious that \(G_l\) is strongly related to the net radiation over the lake with very high correlation coefficients. Figs. 8 and 9 show the comparison between residual \(G_l\) and predicted equation values of \(G_{lp}\).
DURING DAYTIME

\[ G = -68.5 + 0.908 R_n \]
\[ R^2 = 0.983 \]

DURING NIGHTTIME

\[ G = 7.8 + 1.2 R_n - 22.6 U \]
\[ R^2 = 0.89 \]

FIGURE 8. Comparison of Residual Measured and Predicted Water Heat Fluxes over the Lake.
To check the accuracy of this procedure, $G_{1p}$ was compared with the rate of change in heat stored in the lake estimated from the water temperature profile measurements in the deepest point in the lake. Because the water temperature profile measurement was taken once per 3 to 4 weeks, it was difficult to compare $G_1$ on an hourly or daily basis. However, the calculated average rates during these intervals compared well with the average predicted values of $G_{1p}$ during the same periods for both 1993 and 1994 summers as shown in Figs. 10 and 11.

The lake heat flux prediction equations (Eqs. 57-59) are evaluated for Bear Lake, which is a large lake (average depth of about 30 m) with huge capacity to store energy during daytime, leaving a small portion for both LE and H fluxes. It should be noted that these prediction equations may not be suitable for shallow lakes, ponds, and wetlands where water depth is much smaller with lower heat storage capacity during daytime, allowing more energy available for LE and H fluxes.

**Latent Heat and Sensible Heat Fluxes**

Latent heat flux, LE, or evaporation was measured directly using the Eddy Correlation system. Also, using the BR system measurements along with net radiation measurements, and $G_{1p}$ equations, LE was estimated as:

$$LE = \frac{R_n - G_{1p}}{1 + BR}$$  (60)
FIGURE 10. Accumulated Change in Heat Stored in the Lake Versus Depth.
LE from BR calculations (Eq. 60) compared well with independent measurements of LE from the Eddy Correlation system as shown in Fig. 12. However, the plot shows some variations between the two systems when LE rates exceeded about 150 Wm\(^{-2}\). After analyzing the two-system data, it was clear that the BR system overestimated LE rates (by about 15\%) compared to the EC system when wind speeds exceeded about 7 ms\(^{-1}\). This may be due to errors in estimating the Bowen Ratio (H/LE) from the BR system with high wind speeds, which tend to disturb the gradient measurements of both heat and water vapor. This disturbance is due to the good mixing of the air induced by high wind speeds, which makes the measurement profile of air temperature, as well as the profile of water vapor of the air, at the two measurement heights be quite close. As a result, the noise (error) associated usually with these kind of measurements becomes significant. The ratio of sensible heat flux, H, to latent heat flux, LE, from the Eddy Correlation system compared quite well with BR from the Bowen Ratio system as shown in Fig. 13 (also, see Fig. C3 in Appendix C for the Bowen Ratio comparison with time). The above results show the good agreement between the two systems in estimating the surface fluxes from the lake.

Hourly variations of the energy balance components over the lake for selected days of 1993 and 1994 are shown in Fig. 14. The graph shows how water absorbs and transfers downward most of the energy received from the sun compared to soil

FIGURE 13. Comparison of BR System and EC System Measurements.
FIGURE 14. Hourly Energy Budget over the Lake Based on Eddy Correlation Measurements.
and/or vegetation covers. Also, it shows the continuity of evaporation during nighttime when $R_n$ was negative. To emphasize the above findings, Fig. 15 is presented to show the daily energy budget over the lake. Also, to show the diurnal variations of energy balance components over the lake, Fig. 16 is presented to show the energy balance components during daytime (when $R_n>0$), while Fig. 17 represents the energy balance components during nighttime (when $R_n<0$).

The above mentioned plots show a very interesting phenomenon. Contrary to the diurnal evapotranspiration (Et) over soil and/or vegetation where nighttime Et amounts to about 2% and about 98% at daytime, diurnal evaporation over the lake is much smoother since nighttime evaporation was about 45% of the daily total. This phenomenon suggests that, over the lake, evaporation is not a direct function of solar energy received (see Fig. 15 day 172). However, during daytime hours a large portion of solar energy goes to heat the water body of the lake (about 85% of total energy received), while the remaining energy goes to both sensible and latent heat fluxes. This explains why the evaporation rate over the lake is much lower than Et over some vegetative areas. More surprisingly, during nighttime hours evaporation continues almost with the same intensity as daytime hours. The driving energy of nighttime evaporation is conducted directly from the huge amount of heat stored in the water body during the daytime. The energy storage in the lake ensures continuity of
FIGURE 15. Daily Energy Budget over the Lake Based on Eddy Correlation Measurements.
FIGURE 16. Daytime (Rn>0) Energy Budget over the Lake Based on Eddy Correlation Measurements.
Figure 17. Nighttime (Rn<0) Energy Budget over the Lake Based on Eddy Correlation Measurements.
evaporation during nighttime. The lake water body may be considered as an energy buffer that controls the driving energy of evaporation and maintains this interesting evaporation mechanism over the lake.

This smooth diurnal evaporation mechanism may be clarified by studying the daily thermal cycle in the lake. Fig. 18 shows the daily cycle of air, dew point, and water surface temperatures over the lake. Note that having the dew point temperature lower than the surface temperature during daytime as well as nighttime may help explain the above diurnal lake evaporation mechanism. By pointing out that having enough vapor pressure gradient during nighttime along with the available energy released from the huge heat storage in the lake (which was absorbed and stored during daytime), it is clear how the variation in heat storage in the water body governs the diurnal lake evaporation.

In fact, this interesting evaporation mechanism applies to most of the high-latitude lakes, which have a vast yearly storage heat variation cycle, ranging from freezing during winter seasons to reasonably warm water during the summer seasons. However, low latitude or tropical lakes, which have a small yearly storage heat variation cycle, may have a different mechanism of evaporation, which needs to be studied and evaluated.
FIGURE 18. Hourly Comparison of Air Temperature, Dew Point Temperature, and Water Surface Temperature over the Lake.
Estimates Of Evaporation

Factors to be considered in estimation of lake evaporation related parameters include fetch requirements, climatic parameters, aerodynamic resistance, and roughness length parameters. A brief consideration of each, relative to this study, follows.

Fetch Requirements

To ensure a good quality of collected data free from lake-unrelated advection problem, the data were filtered to account for suitable fetch requirements even though the measurement location was over water at least 150 m from the north shore. Data were rejected when prevailing winds were blowing from about a 90° arc (northwest to northeast) and accepted otherwise. However, the data analysis showed no noticeable variations between measured and estimated lake evaporation parameters even when prevailing winds were blowing from the northwest to northeast arc direction. This may be due to the Mud Lake effect, which is located to the north close enough to the study measurement location (see Fig. 1). It is believed that both lakes, Bear Lake and Mud Lake, have similar conditions. Thus, the measurement location was suitable (except for the EC system) for collection of data that represents the lake environment regardless of wind direction.
Climatic Parameters

To estimate lake evaporation using different evaporation methods, climatical parameters are needed. These parameters include latent heat of vaporization, psychometric constant, slope of saturation vapor pressure curve, saturation vapor pressure deficit, maximum possible clear sky solar radiation, and others. Meteorologic data are required to estimate these climatic parameters. Procedures of calculations of these parameters are well documented in many reference books in the literature. In this study procedures presented in ASCE manual 70 (Jensen et al., 1990) and ICID bulletin (Allen et al., 1994) were adapted to estimate different climatical parameters.

Concerning the estimation of actual vapor pressure of the air, $e_d$, required in Penman-type equations and after comparing different procedures reported in the literature with actual air vapor pressure measured from BR system, the following procedure was adapted:

For hourly data:

$$ e_d = RH_a \times e_s(T_a) $$  \hspace{1cm} (61)

For daily data:

$$ e_d = RH_x \times e_s(T_m) $$  \hspace{1cm} (62)
where $\text{RH}_a$ and $\text{RH}_x$ are average and maximum relative humidity of the air, respectively; and $e_s(T_a)$ and $e_s(T_x)$ are saturation vapor pressure at average and minimum air temperature, respectively.

**Aerodynamic Resistance and Roughness Parameters**

To use aerodynamic Penman-type equations to predict evaporation from lakes, it is necessary to estimate the aerodynamic resistance term $r_a$. However, to achieve a good estimation of $r_a$, it is important to evaluate the values of roughness length of momentum $z_{om}$ and roughness length of heat $z_{oh}$ parameters.

No comprehensive studies with actual measurements were reported to determine the values of roughness length parameters over water. Moreover, the values of $z_{om}$ over water reported in the literature vary greatly. This made it difficult to estimate which value was suitable for this study. As a result and because no actual measurements of wind profile or $u_*$ were taken, a backward procedure was followed to find the values of roughness length parameters.

From measurements of LE, $R_n$, $G_t$, and over-lake climatological data, the aerodynamic component of the Penman equation $LE_{aero}$ was estimated as a residual as follows:

$$LE_{aero} = LE - \frac{\Delta (R_n - G_t)}{\Delta + \gamma} \quad (63)$$
Fig. 19 shows the comparison between residual $\text{LE}_\text{aero}$ and wind speed. The aerodynamic resistance term $r_a$ was estimated by arranging residual $\text{LE}_\text{aero}$ terms (Eqs. 22 and 63) as follows:

$$r_a = \frac{1}{\Delta + \gamma} \frac{\rho C_p}{\text{LE}_\text{aero}} (e_s - e_d) \quad (64)$$

Estimated $r_a$ was plotted against wind speed as shown in Fig. 20. The above-mentioned two plots imply that lake evaporation was related in a general way to wind speed. Wind effect can be easily explained, since wind induces more turbulence, which enhances water vapor transport. In other words, as wind increases, aerodynamic resistance for water vapor decreases, which means more evaporation (see Fig. 20). Also, wind enhances the horizontal advection of heat and humidity, and the vertical transport of saturation deficit from the drier air aloft. Hence, the wind may affect the saturation deficit, which in turn may affect the evaporation rates.

By using estimated $r_a$ values (Eq. 64) and wind speed measurements, an iterative solution was followed to solve for $z_{om}$ using Eq. (43). In this iterative procedure, $\psi_m$ and $\psi_h$ stability correction integral functions were a) estimated as zero for the neutral atmospheric condition, b) calculated using the exact solution as a function of the bulk Richardson number following Choudhury et al. (1986) for stable atmosphere condition, and c) calculated using the analytical solution.

FIGURE 20. Residual Measured Aerodynamic Resistance ($r_a$) Versus Wind Speed.
assuming flux Richardson number equals bulk Richardson number following Byun (1990) for unstable atmospheric condition (see Fig. C4 in Appendix C for comparison with iteration procedure as function of Monin-Obukhov length). Also, three cases of $z_{om}$ to $z_{oh}$ ratios were tested, the ratios being 10 to 1, 1 to 2, and 1 to 3. The 10 to 1 ratio represents the well-known $z_{om}$ to $z_{oh}$ ratio widely used in agronomy applications, while the other two $z_{om}$ to $z_{oh}$ ratios represent the expected theoretical ratios given by Garratt (1992) and Brutsaert (1982), respectively, for water.

A $z_{om}$ to $z_{oh}$ ratio of 1 to 3 was chosen because it gave the least scattered backward residual estimate of roughness length of momentum $z_{om}$. The residual and theoretical (Eq. 39) estimates of $z_{om}$ versus wind speed are shown in Fig. 21. This plot shows how residual measurements of momentum roughness length agreed quite well with the theoretical values. However, some of the calculated $z_{om}$ values by residual seem to be lower than the corresponding theoretical values (Eq. 39). This may be due to stability effect or, as reported by Brutsaert (1982), because the water may behave as a super-smooth surface. Moreover, the plot shows how the roughness length of momentum decreases with wind speed, suggesting that the lake surface behave as a smooth surface (see the literature review section). It is expected that the water surface will behave as a rough surface when wind speeds reach a critical value. However, in this study measurements did not reach that
critical wind speed value even though a wind speed of up to 9 ms\(^{-1}\) was measured. However, having most of the wind speed measurements under 5 ms\(^{-1}\), and just few scattered measurements over that value, made it difficult to get any conclusive critical wind speed value.

Also, based on the theoretical roughness parameter of smooth surface in Eq. (39), aerodynamic resistance \(r_a\) was estimated using Eq. (24) where stability was not considered and Eq. (43) where stability correction was considered. The comparison of residual and estimated \(r_a\) with and without stability correction versus wind speed is shown in Fig. 22. This plot shows how stability had some effect on calculations of \(r_a\).

In fact, since the roughness length of momentum, as well as other roughness length parameters, is so small compared to vegetation values, this may be related to the large values of aerodynamic resistance over the lake compared to vegetation (see Fig. 22). Also, this may explain why the intensity of evaporation over the lake is much less than vegetative \(E_t\) as shown in the previous section. Moreover, studying Fig. 18 once again, one can show how stability variations over the lake can be related to the diurnal lake evaporation as mentioned earlier. In fact, having the water surface temperature higher than the air temperature during the nighttime causes an unstable atmospheric condition, which enhances the water vapor transport by decreasing the
FIGURE 21. Comparison of Residual and Calculated (Eq. 39) Aerodynamic Roughness Length of Momentum \((z_{om})\) Versus Wind Speed.

FIGURE 22. Comparison of Residual and Calculated Aerodynamic Resistance \((r_a)\) Versus Wind Speed.
aerodynamic resistance. On the other hand, during the daytime hours, the air-water temperature pattern induces a stable atmospheric condition, which reduces the water vapor transport by increasing the aerodynamic resistance. The above factors, along with the role of heat storage in the lake explained previously, may explain why and how evaporation from the lake is lower in intensity and has smoother diurnal variation compared to vegetation.

As mentioned earlier and as shown in Fig. 22, aerodynamic resistance for water vapor decreases as wind speed increases. However, as wind speed reaches about 5 ms\(^{-1}\), any further increases in wind speed have minimal effect on aerodynamic resistance \( r_a \). Also, over the same wind speed value, 5 ms\(^{-1}\), the effect of stability seems to vanish since neutral atmospheric condition dominates. This point may be clarified from Fig. 23, which shows the relation between Richardson number and wind speed. The plot shows how \( R_i \) approaches zero as wind speed increases, which indicates that as wind speed increases the friction force (turbulence effect) increases while the buoyancy force decreases, making their ratio (buoyancy force to friction force) approach zero. The above discussion may suggest an upper limit of wind speed over which lake evaporation will not be affected very much by stability.
FIGURE 23. Relation Between Bulk Richardson Number and Wind Speed Based on Hourly Data.
CHAPTER V
LAKE EVAPORATION METHOD COMPARISON

Method Comparison

Actual estimates of evaporation from the lake using both the Eddy Correlation and Bowen Ratio systems were the basis on which other evaporation estimates were compared. As shown in the previous chapter, the similarities of both system estimates make their measurements a reliable basis to judge other evaporation estimate performances.

The methods analyzed in this study along with the required input data and calculation time step tested are given in Table 1. Also, the last column of Table 1 shows the methods' parameters that were modified based on the results from this study. An evaporation model (EVAPMODL) program was written that gives the best lake evaporation estimates utilizing the above-mentioned adapted methods (Table 1). The program can accept both hourly or daily weather data as inputs for Penman-type equations (i.e., T, RH, u, and Rs). Also, in case of availability of measurements of either Ts and/or Rs, the program may use these measurements for better estimates of lake evaporation. A flowchart, description, and listing of the EVAPMODL program are in Appendix B. Method comparison results are presented in this section. Discussion of the performance of each method is presented in the next section.
TABLE 1. List of Lake Evaporation Methods Tested.

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
<th>Input data</th>
<th>Time step</th>
<th>Approach</th>
<th>Modified parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lakshman</td>
<td>Eq. (5)</td>
<td>T, RH, u</td>
<td>Hourly, Daily</td>
<td>Mass transfer</td>
<td></td>
</tr>
<tr>
<td>Kohler-Nordenson-Fox</td>
<td>Eq. (17)</td>
<td>T, RH, u, Rs</td>
<td>Daily</td>
<td>Combination-Theoretical pan</td>
<td>Rn</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>Eq. (19)</td>
<td>T, RH, u, Rs</td>
<td>Hourly, Daily</td>
<td>Combination-Wind function</td>
<td>Rn, GI</td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td>Eq. (22)</td>
<td>T, RH, u, Rs</td>
<td>Hourly, Daily</td>
<td>Combination-Aerodynamic resistance</td>
<td>Rn, GI, ra</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>Eq. (26)</td>
<td>T, Rs</td>
<td>Hourly, Daily</td>
<td>Radiation</td>
<td>Rn, GI</td>
</tr>
<tr>
<td>Morton</td>
<td>Eq. (27)</td>
<td>T, RH, Rs</td>
<td>Daily</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td>Pan Conversion</td>
<td>Eq. (44)</td>
<td>Class A pan evaporation</td>
<td>Daily</td>
<td>Pan conversion</td>
<td></td>
</tr>
</tbody>
</table>

T = Air temperature.  
RH = Air relative humidity.  
u = Wind speed.  
Rs = Solar radiation.  
Rn = net radiation.  
GI = lake heat flux.  
ra = aerodynamic resistance.

* These are the parameters that were modified based on the results obtained from this study.
Over-Lake comparison

Lake evaporation estimates were evaluated using weather data measured over the lake. $R_n$ was either measured or estimated as Eq. (50) (when $T_s$ is available), and $G_1$ was estimated as Eqs. (57-59). In this study, the stability effect on evaporation was evaluated. The study showed the importance of applying stability correction for small time-step calculations. Fig. 24 shows hourly comparison of the Penman-Monteith estimate of lake evaporation with stability correction (Eq. 43 following Choudhury et al. (1986) for stable atmospheric condition and Byun (1990) for unstable atmospheric condition) and without stability correction (Eq. 24). When estimating aerodynamic resistance, $z_{om}$ was calculated as Eq. (39). As a result of this comparison, the stability correction was applied to the Penman-Monteith equation whenever applicable (i.e., in case of hourly time-step calculations and availability of water surface temperature $T_s$). Hourly evaporation as estimated by different methods is compared with measured values using over-lake data as shown in Fig. 25. Daily comparison is shown in Fig. 26.

Nearby Land-Based Comparison

Nearby land-based weather data from two electronic weather stations, namely Garden City and the Lifton, were analyzed to test if their data were suitable as inputs for different method estimates of lake evaporation. Both land-
based station sites were not preferable, since they were close to some trees and/or buildings. Moreover, the Lifton weather station was surrounded by two lakes (Bear Lake and Mud Lake), which made its data represent over-lake measurements regardless of wind direction. As a result, Garden City station was considered the only nearby land-based weather station when prevailing winds were blowing from about a 90° arc (southwest to northwest). However, because weather data from Garden City station were available only during summer 1993, there were about 21 days worth of data suitable for the land-based comparison during this study.

Weather data from the Garden City land-based station were compared to the over-lake weather data collected during this study. Land-based measurements of air temperature, relative humidity, and solar radiation compared well with over-lake measurements as shown in Figs. 27 and 28. However, land-based measurements of wind speed from Garden City station were lower than over-lake measurements most of the time (see Fig. 28). Even though the two anemometers used for wind measurements were not similar, this difference in wind measurements reflects the difference between over-lake and land environments. The overall ratio between $u_{\text{lake}}$ to $u_{\text{land}}$ was estimated to be about 1.55 (after adjusting for height differences using Eq. 7.24 in ASCE manual 70). This ratio (1.55) agreed quite well with the calculated $u_{\text{lake}}$ to $u_{\text{land}}$ ratio
FIGURE 27. Comparison of Over-Lake and Land-Based Measurements of Minimum and Maximum Daily Temperature and Relative Humidity of the Air.
of about 1.5 from application of Eq. (4.181) of Allen and Pruitt (in print) (Dr. Richard G. Allen, personal communication, 1995).

When using land-based weather data as input for estimating lake evaporation, $R_n$ was estimated as Eq. (35) (when $T_s$ is not available) with $a_1$, $b_1$, $a$, and $b$ coefficients as given by Eqs. (52-53). Daily evaporation as estimated by different methods is compared with actual evaporation measurements using the Garden City station as shown in Fig. 29. A comparison between land-based class A pan evaporation and measured lake evaporation is shown in Fig. 30 for 1994, June through August. Also, Fig. 31 is presented to show the comparison of lake evaporation using the Penman-Monteith method for lakes ($L_{P-M}$), grass reference ET ($ET_0$), and pan evaporation ($E_{pan}$) for 1994, March 3 to October 26.

The relatively low evaporation rates from the lake compared to $E_{pan}$ or $ET_0$ are evident in Figs. 29-31. Moreover, the estimated lake evaporation during this study (2 mm/day, Mar.-Oct. average) is about 50% lower than many traditional water-budget estimates previously reported. For example, annual averages were 3.7 mm/day at Lake Hefner, Oklahoma; 4.9 mm/day at Salton Sea, California; and 3.5 mm at Pyramid and Winnemucca Lakes, Nevada (Maniciano and Harbeck, 1954; Kohler et al., 1955; Morton, 1979). However, similar results (annual averages of 1.9-2 mm/day) to those found at Bear Lake were
FIGURE 30. Comparison of Land-Based Class A Pan Evaporation Measurements and Lake Evaporation Measurements from Bowen Ratio System.
FIGURE 31. Comparison of Lake Evaporation from Penman-Monteith Equation (LE$_{p-m}$), Grass Reference ET (ET$_0$), and Pan Evaporation (E$_{pan}$) During Mar. 3 to Oct. 26, 1994.
reported for Lake Ontario and Dauphin Lake, Canada (Morton, 1979). Moreover, recent evaporation measurements from Utah Lake during summer 1994 using an Eddy Correlation system showed quite similar results to this 2-year study. Low evaporation rates were found that were not correlated directly to $R_n$ since the heat flux into the lake (Utah Lake) represented a large portion of the energy received (Dr. Lawrence E. Hipps, personal communication, 1995).

In an attempt to compare the expected evaporation rates from the lake to vegetation ET in a yearly cycle, Fig. 32 is presented to show the comparison of $LE_{p,M}$ and $ET_0$ for the year 1993 using Lifton station weather data. Note that land-based wind speeds from Lifton station were adjusted to reflect over-lake conditions by multiplying by a factor of 1.7 when estimating lake evaporation (see Figs. C5-C6 in Appendix C for comparison of over-lake and Lifton station weather data). This plot (Fig. 32) shows clearly the trade-off between $LE_{p,M}$ and $ET_0$ during summer and winter months. As a further step in this analysis, Appendix D is presented to show the expected yearly energy budget over the lake using Lifton station weather data. The analysis in Appendix D shows the importance of sensible and latent heat fluxes as well as outgoing longwave radiation (negative $R_n$) as the main sinks of the heat absorbed and stored in the lake during summer months.
FIGURE 32. Comparison of Lake Evaporation Using Penman-Monteith Method (LE<sub>p-M</sub>) and Reference Grass ET (ET<sub>o</sub>) for 1993 Land-Based Lifton Station Weather Data.
Statistical Study

The estimates given by different methods were statistically compared to evaporation measurements by calculating the means, coefficient of determinations $R^2$, standard error of estimates $SEE$, and coefficients of variation $CV$. The comparison was based on daily time step calculations and covered both over lake and nearby land-based measured weather data.

Comparisons of estimates using over lake data for both summers of 1993 (Aug. 17 - Oct. 22) and 1994 (Mar. 3 - Oct. 26), respectively, are in Tables 2 and 3. Table 4 shows comparison of estimates using Garden city weather data during summer 1993 (21 days during the period Aug. 17 to Oct. 22).

Method Performance

As shown in the previous section, some methods performed well compared to measurements in both hourly and daily time step calculations, while the performance of other methods was lower than expected. In general, as shown in Figs. 25 and 26, combination or Penman-type methods compared well to actual measurements, while the pan conversion method was unsuccessful even in matching the general evaporation trend from the lake (see Figs. 30-31). Performance of other methods was acceptable for some situations and unacceptable for others. However, it should be noted that since heat flux to the lake, $G_1$, is the largest term by far, any approach where evaporation is a

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean (mm/day)</th>
<th>Total (mm)</th>
<th>Ratio</th>
<th>R2</th>
<th>SEE (mm/day)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>1.9</td>
<td>129.8</td>
<td>1.00</td>
<td>1.000</td>
<td>0.000</td>
<td>19.8</td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td>1.9</td>
<td>127.8</td>
<td>0.98</td>
<td>0.905</td>
<td>0.113</td>
<td>18.9</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>1.9</td>
<td>126.9</td>
<td>0.98</td>
<td>0.893</td>
<td>0.155</td>
<td>24.7</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>1.8</td>
<td>123.5</td>
<td>0.95</td>
<td>0.652</td>
<td>0.120</td>
<td>10.8</td>
</tr>
<tr>
<td>Morton</td>
<td>1.5</td>
<td>99.1</td>
<td>0.76</td>
<td>0.326</td>
<td>0.530</td>
<td>43.0</td>
</tr>
<tr>
<td>Kohler-Nordenson-Fox</td>
<td>1.5</td>
<td>101.7</td>
<td>0.78</td>
<td>0.526</td>
<td>0.572</td>
<td>53.9</td>
</tr>
<tr>
<td>Lakshman</td>
<td>1.5</td>
<td>99.7</td>
<td>0.77</td>
<td>0.724</td>
<td>0.346</td>
<td>43.6</td>
</tr>
</tbody>
</table>

**Ratio** = Ratio of mean of the estimate to mean of the measured.

**R2** = Coefficient of determination of the estimate related to the measurements.

**SEE** = The standard error of the estimate.

**CV** = Coefficient of variation.

**Note:** Mean ETo during the same period was 2.9 mm/day

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean (mm/day)</th>
<th>Total (mm)</th>
<th>Ratio</th>
<th>R2</th>
<th>SEE (mm/day)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>2.0</td>
<td>480.0</td>
<td>1.00</td>
<td>1.00</td>
<td>0.000</td>
<td>24.3</td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td>2.0</td>
<td>469.4</td>
<td>0.98</td>
<td>0.861</td>
<td>0.167</td>
<td>22.6</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>2.0</td>
<td>466.7</td>
<td>0.97</td>
<td>0.839</td>
<td>0.221</td>
<td>28.0</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>2.0</td>
<td>478.2</td>
<td>1.00</td>
<td>0.792</td>
<td>0.153</td>
<td>16.6</td>
</tr>
<tr>
<td>Morton</td>
<td>2.0</td>
<td>480.3</td>
<td>1.00</td>
<td>0.380</td>
<td>0.658</td>
<td>41.3</td>
</tr>
<tr>
<td>Kohler-Nordenson-Fox</td>
<td>2.2</td>
<td>531.0</td>
<td>1.11</td>
<td>0.557</td>
<td>0.768</td>
<td>51.3</td>
</tr>
<tr>
<td>Lakshman</td>
<td>1.5</td>
<td>368.5</td>
<td>0.77</td>
<td>0.705</td>
<td>0.421</td>
<td>49.8</td>
</tr>
</tbody>
</table>

Ratio = Ratio of mean of the estimate to mean of the measured.
R2 = Coefficient of determination of the estimate related to the measurements.
SEE = The standard error of the estimate.
CV = Coefficient of variation.

Note: Mean ETo during the same period was 3.7 mm/day

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean (mm/day)</th>
<th>Total (mm)</th>
<th>Ratio</th>
<th>R2</th>
<th>SEE (mm/day)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>2.1</td>
<td>44.9</td>
<td>1.00</td>
<td>1.000</td>
<td>0.000</td>
<td>12.5</td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td>2.0</td>
<td>41.9</td>
<td>0.93</td>
<td>0.716</td>
<td>0.149</td>
<td>13.4</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>2.1</td>
<td>43.2</td>
<td>0.96</td>
<td>0.694</td>
<td>0.207</td>
<td>17.3</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>2.0</td>
<td>42.5</td>
<td>0.95</td>
<td>0.541</td>
<td>0.123</td>
<td>8.5</td>
</tr>
<tr>
<td>Morton</td>
<td>1.9</td>
<td>39.3</td>
<td>0.88</td>
<td>0.128</td>
<td>0.489</td>
<td>26.6</td>
</tr>
<tr>
<td>Kohler-Nordenson-Fox</td>
<td>2.0</td>
<td>42.0</td>
<td>0.93</td>
<td>0.142</td>
<td>0.650</td>
<td>33.4</td>
</tr>
<tr>
<td>Lakshman</td>
<td>1.1</td>
<td>23.7</td>
<td>0.53</td>
<td>0.433</td>
<td>0.327</td>
<td>36.6</td>
</tr>
</tbody>
</table>

Ratio = Ratio of mean of the estimate to mean of the measured.
R2 = Coefficient of determination of the estimate related to the measurements.
SEE = The standard error of the estimate.
CV = Coefficient of variation.
function of \((R_n - G_i)\) would predict fairly well. Detailed analysis of the performance of each method tested in this study follows.

**Lakshman**

Although this method uses the variable mass transfer constant \((N)\) as a function of lake size and wind speed, it underestimated evaporation from the lake by about 20-40% in daily calculations. The method gave better results in case of hourly time step calculations as shown in Fig. 25. However, the requirement of having water surface temperature on an hourly basis limits the practical usage of this method in most situations. When nearby weather data were used, the water surface temperature was assumed equal to the average of air temperature of the three previous consecutive days. However, this assumption made this method underestimate the lake evaporation by about 50-60% (see Fig. 29).

**Kohler-Nordenson-Fox**

Daily estimation of lake evaporation using this method gave moderate results when compared to actual measurements. In general, this method underestimated the evaporation from the lake by about 40-70% for some situations while for others it overestimated the evaporation by the same percentage with a moderately low coefficient of determination of about 0.5. In fact, this method theoretically estimates the evaporation from a pan, then relates it to the lake evaporation by multiplying
by a factor of 0.7. In this study both net radiation and wind speed used as input for this method either were measured over the lake in case of over lake comparison, or estimated to reflect lake environment in case of land-based comparison. Usually these factors are measured or estimated over the pan environment. It is expected if net radiation is estimated or measured over the pan it would be lower than $R_n$ over the lake. The same expectation stands for pan height wind speed. As a result, the over all lake evaporation estimated by this method would be lower.

**Penman-Lake**

This method was adapted originally from the Kohler-Nordenson-Fox method to estimate lake evaporation using data required by Penman-type equations. The Penman-Lake method compared quite well with actual measurements in both hourly and daily time-step calculations. However, in hourly calculations the method seemed to overestimate the lake evaporation by about 20%. On the other hand, when using land-based weather data this method seemed to underestimate the evaporation from the lake by about 5-10% on a daily basis. However, this result was expected since the land-based wind speed measurements were about 50% lower than over-lake measurements most of the time as mentioned previously.
Penman-Monteith

The ability of this method to account for aerodynamic resistance made it compare well with actual measurements in both hourly and daily time-step calculations. In reality this equation showed a strong agreement with actual measurements when appropriate roughness length parameters and atmospheric stability corrections (in case of hourly calculations) were applied. This reflects the ability of this method to estimate the evaporation from the lake with high accuracy when the input parameters evaluated properly (see Figs. 25 and 26). Although some deviations from actual measurements showed up when nearby land-based weather data were used (see Fig. 29), this may be related to the over-lake and land-based wind speed differences as explained earlier.

Priestley-Taylor

In this study the Priestley-Taylor method was calibrated by determining the coefficient $a$ for both hourly and daily time-step calculations. The calibration was possible by using actual lake evaporation measurements and applying simple linear regression through the origin. The coefficients were determined to be 1.30 and 1.42 for hourly and daily time-step calculations, respectively. These coefficients are slightly higher than the 1.26 equilibrium coefficient reported in the literature in the case of widely uniform vegetative areas. These higher values of the Priestley-Taylor coefficients
account for the omitted Penman-type aerodynamic term. This reflects the importance of the wind or aerodynamic term with respect to the radiation term in case of lake evaporation compared to the equilibrium Et for vegetation.

Using the new calibrated coefficients, the Priestley-Taylor method performed quite well in both hourly and daily time-step calculations. However, this method seems to underestimate the evaporation by 10-20% when lake evaporation exceeded 2 mm per day and vice versa. Nevertheless, this method is considered a good option when there are no sufficient data available to use Penman-type equations.

Morton

This method was originally developed to estimate evaporation from lakes on a monthly time-step basis. However, in this study the Morton method was adapted for daily time-step estimation of lake evaporation. The general performance of this method was quite low when compared to actual measurements. In general, the Morton method underestimated the evaporation from the lake by 30-70% for some situations while it overestimated the evaporation by 20-50% for others with a very low coefficient of determination of about 0.35. A trial to test the performance of this method for monthly time-step calculation was made. Surprisingly, the test indicated that the method tended to overestimate the evaporation from the lake by about 50%.
Pan Conversion

This method provided highly unexpected results when compared to actual evaporation measurements over the lake. Many efforts were unsuccessful when trying to choose a suitable pan coefficient to relate pan evaporation to lake evaporation (see Fig. 30). This significant difference in the evaporation pattern between the pan and lake environments, again, reflects the huge differences between the pan and lake energy budget and evaporation mechanism in both systems. Apparently, the pan seems to respond directly to the total energy received as solar radiation on a daily basis. However, as previously mentioned, the lake does not have that direct relation. In general, the theoretical pan coefficient during this study ranged from about 0.20 to 1.30, which represents sunny to cloudy sky situations. During the 1994 season the overall ratio of lake evaporation to pan evaporation was about 0.4, which is considered to be less than the literature-reported ratio of about 0.7.

Method Selection

Based on the previous method comparison section, the methods were compared according to their ability to estimate the evaporation from the lake. The statistical study results, which are summarized in Tables 2 and 3, were the basis to select the suitable methods for future estimation of evaporation from the lake. The factors that had been checked
and compared were the mean, coefficient of determination, standard error of estimate, and coefficient of variation. Based upon the above criteria, Table 5 lists the methods in the order of their rank in estimating lake evaporation. When using nearby land-based weather data, most of the tested methods showed almost the same trend and ability to estimate lake evaporation as when using over-lake data. However, due to the existence of some differences between over-lake and land-based weather data measurements (mainly wind speed), some equations lost part of their accuracy in matching the actual lake evaporation.

From Table 5, the first three methods seem to reflect the evaporation mechanism in the lake, so they are recommended in this study. The usage of other methods tested may result in errors of about ±40-70% of actual lake evaporation.

Sensitivity Analysis

In practice, collected weather data are subjected to different types of errors due to the sensor inherent accuracy, calibration error, aging, and many others. Usually an error of 5-10% is expected from sensors normally used in electronic weather stations. Since weather data are the main input parameters for different evaporation estimate methods, it is good to know how sensitive these equations are to errors in the collected input parameters.
<table>
<thead>
<tr>
<th>Method</th>
<th>Mean (mm/day)</th>
<th>R2</th>
<th>SEE (mm/day)</th>
<th>CV (%)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>2.00</td>
<td>1.000</td>
<td>0.000</td>
<td>23.3</td>
<td></td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td>1.96</td>
<td>0.871</td>
<td>0.155</td>
<td>21.8</td>
<td>1</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>1.95</td>
<td>0.851</td>
<td>0.207</td>
<td>27.3</td>
<td>2</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>1.97</td>
<td>0.762</td>
<td>0.146</td>
<td>15.3</td>
<td>3</td>
</tr>
<tr>
<td>Kohler-Nordenson-Fox</td>
<td>2.08</td>
<td>0.550</td>
<td>0.725</td>
<td>51.9</td>
<td>4</td>
</tr>
<tr>
<td>Lakshman</td>
<td>1.53</td>
<td>0.709</td>
<td>0.405</td>
<td>48.4</td>
<td>4</td>
</tr>
<tr>
<td>Morton</td>
<td>1.90</td>
<td>0.368</td>
<td>0.630</td>
<td>41.7</td>
<td>4</td>
</tr>
</tbody>
</table>
The three recommended equations were selected to perform the sensitivity analysis. These equations are Penman-Lake, Penman-Monteith, and Priestley-Taylor. The analysis was based on daily time-step calculations using 1993 over-lake weather data (August 17 to October 22). Each parameter of the input data was changed by ±5, ±10, and ±20 percent to examine the effect on evaporation estimates. Also, the effect of having the worst combination of all parameters was tested. Results are given in Table 6. Also, the results of Table 6 are graphically clarified by presenting Fig. 33. The presented results show how method estimates are sensitive to any input parameter error or combination of parameter errors.

Both Penman-Monteith and Penman-Lake equations were very sensitive to any errors in temperature or relative humidity parameters. However, relative humidity has an opposite trend compared to temperature (see Fig. 33). Both equations seem to be half as sensitive to wind speed as compared to temperature or relative humidity. The Priestley-Taylor equation was moderately sensitive to temperature, and as expected insensitive to either relative humidity or wind speed. The three equations, again, reflected the previously described evaporation mechanism in the lake by showing very low sensitivity to the solar radiation parameter.

Note that since relative humidity has an opposite trend compared to other input parameters, errors in the evaporation estimate methods due to errors in combination of two or more
TABLE 6. Sensitivity of Method Estimates as Percentages Due to Errors in the Input Parameters.

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter Error</th>
<th>T</th>
<th>RH</th>
<th>u</th>
<th>Rs</th>
<th>All Parameters</th>
<th>Worst Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penman-Monteith</td>
<td>+5%</td>
<td>2.1</td>
<td>-1.8</td>
<td>1.2</td>
<td>0.2</td>
<td>1.7</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>+10%</td>
<td>4.2</td>
<td>-3.5</td>
<td>2.4</td>
<td>0.3</td>
<td>3.5</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>+20%</td>
<td>8.5</td>
<td>-6.9</td>
<td>4.8</td>
<td>0.6</td>
<td>7.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Penman-Lake</td>
<td>+5%</td>
<td>2.9</td>
<td>-3.0</td>
<td>1.5</td>
<td>0.1</td>
<td>1.5</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>+10%</td>
<td>5.8</td>
<td>-6.0</td>
<td>3.0</td>
<td>0.2</td>
<td>3.0</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>+20%</td>
<td>11.5</td>
<td>-11.7</td>
<td>6.0</td>
<td>0.4</td>
<td>6.2</td>
<td>29.0</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>+5%</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>+10%</td>
<td>2.4</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.4</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>+20%</td>
<td>4.8</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.8</td>
<td>5.7</td>
<td>6.0</td>
</tr>
</tbody>
</table>

T = Air temperature.
RH = Air relative humidity.
u = Wind speed.
Rs = Solar radiation.
All Parameters = T, RH, u, and Rs having the same error (i.e., error has the same magnitude and sign).
Worst Combination = Combination of all parameter with same magnitude of error but with RH having opposite error sign.

* In case of negative parameter error (i.e., -5%, -10%, and -20%), the table can be accessed by multiplying the estimate error by (-1).
FIGURE 33. Sensitivity of Selected Methods as Percentages Due to Errors in the Input Parameters.
input parameters may either be subtracted or added, depending on the input parameter error signs. The last two columns of Table 6 show two combination extremes when all input parameters had equal magnitude of error. The first extreme was when all parameter errors had the same sign, while the second extreme was when the error in relative humidity had an opposite sign to the errors in the other input parameters. Table 6 and Fig. 33 show how in the first case, the error in the estimate was about one third of the error in the input parameters for both the Penman-Monteith and Penman-Lake equations. In the second case, the error in the estimate was almost equal in the case of the Penman-Monteith equation, or greater in the case of the Penman-Lake equation, to the error in the input parameters. Since the Priestley-Taylor method is not sensitive to relative humidity and wind speed, both cases gave the same trend where the error in the estimate was about one fourth of the error in the input parameters.
Conclusions

With the aim of gaining a better understanding of evaporation mechanism from a large, free water surface, actual measurements of energy fluxes and meteorological data were made over Bear Lake during the summers of 1993 and 1994. These over-lake measurements along with nearby land-based weather data measurements were used to test and evaluate the ability of existing methods to estimate evaporation from the lake. The ability of the Eddy Correlation system to measure both latent and sensible heat fluxes was the basis on which heat storage in the lake was estimated by residuals. The drawn conclusions from this study are as follows:

1. Evaporation from the lake comprises about 15% of daytime net radiation over the lake, while approximately 85% of daytime net radiation was used in heating the lake water body.

2. Later, during the nighttime, a portion of the daytime stored heat was released in the forms of latent and sensible heat fluxes. This mechanism ensures continuity of lake evaporation throughout the nighttime with approximately the same rate as during the daytime.

3. Evaporation from the lake during the summer season (March-October) averaged about 2 mm/day. This represented
about 30-60% of daily average net radiation.

4. Contrary to the observed evapotranspiration from soil and/or vegetation covers, the evaporation from the lake was not very well directly related to incoming solar radiation. This is because solar radiation on a daily basis is not the only evaporation-driving energy; however, heat storage in the lake is considered another main driving energy for lake evaporation during nighttime or daytime cloudy sky conditions.

5. In this study some lake-related parameters were measured and/or estimated for future use and calibration of existing lake evaporation methods. These include water surface albedo, water roughness length parameters, net radiation over water, and heat storage in the lake.

6. Evaporation from the lake can be estimated with high accuracy if related parameters such as net radiation, heat storage, and aerodynamic effect are evaluated properly to reflect conditions over the lake. Energy approach methods in the form of Penman-type equations seem to work well when over-lake parameters were used. Using other approaches may lead to unacceptable errors in many cases.

7. The Priestley-Taylor method performed quite well even though it requires lower input parameters compared to other methods. Moreover, this method showed less sensitivity to errors in input parameters. As a result,
this method is recommended when there is no sufficient data available to use Penman-type methods or in case of poor quality data.

8. When comparing over-lake and land-based weather parameter measurements, wind speed seems to be the only parameter that had a significant difference of about 50%. Other parameters such as air temperature, relative humidity, and solar radiation seem to have a difference of 5-10%, which is considered to be acceptable in practice. As a result, when using nearby land-based weather data to estimate evaporation from the lake, the wind speed parameter must be adjusted to reflect over-lake conditions.

9. A survey of remotely sensed water surface temperature showed that the lake surface temperature was very uniform and strongly agreed with measurements of water surface temperature using floating thermocouples near the north shore of the lake. This result reflects the well mixed condition in the lake and showed the reliability of using one measurement location of water surface temperature to represent the whole lake.

Recommendations

This study clarified many facts about the evaporation mechanism from the lake and the factors affecting it. In addition, some lake-related parameters were evaluated. Also,
the ability of some existing methods in estimating the evaporation from the lake were tested and evaluated. Hence, the following are some recommendations for future studies:

1. Study the effect of lake size on evaporation. Also, investigate evaporation from low latitude and tropical lakes and try to present a more general form of heat storage in lakes which can be transferable from lake to lake.

2. Study an evaporation mechanism from the lake during the winter season with partial to full ice coverage. Although lake evaporation is expected to be small (about 1 mm/day) during winter months, actual field study is recommended to clarify this point in the future.

3. Study the applicability of using distant land-based weather data to estimate evaporation from lakes. This may be useful in case of no available weather data in the vicinity of a lake.
REFERENCES


APPENDICES
APPENDIX A. Survey of Remotely Sensed Water Surface Temperature
On Sept. 11, 1993 Bear Lake water surface temperatures were remotely sensed. The collected thermal images showed no significant spatial variations of water surface temperatures all over the lake. Eight selected thermal images were chosen for the analysis. These images cover different locations all over the lake including the study measurements site near the north shore (image (a) in Fig. A1). These images were analyzed using ERDAS software package at Biological and Irrigation Engineering (BIE) Remote Sensing Laboratory, USU.

Plates A1 and A2 show the eight thermal images selected. Each image covers about 1 km$^2$ and shows the water surface temperature in a brightness mode. Note that when interpreting these images, one should notice that each image has different brightness-temperature scale. Table A1 shows the average and standard deviation of the remotely sensed water surface temperatures of each image along with the corresponding floating thermocouple measurements of water surface temperatures near the north shore. This table shows the good agreement between the floating thermocouple measurements and the remotely sensed surface temperatures. Also, it reflects the good mixing condition in the lake by showing how the water surface temperatures were uniformly equal all over the lake.
PLATE A1. Bear Lake Thermal Images a, b, c, and d.
PLATE A2. Bear Lake Thermal Images e, f, g, and h.

<table>
<thead>
<tr>
<th>Image location</th>
<th>IMAGE TEMPERATURE SCALE</th>
<th>REMOTELY SENSED SURFACE TEMP.</th>
<th>Measured surface Temp. near the north shore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAXIMUM Brightness</td>
<td>MINIMUM Brightness</td>
<td>AVERAGE Brightness</td>
</tr>
<tr>
<td>a</td>
<td>98.0</td>
<td>16.0</td>
<td>218.0</td>
</tr>
<tr>
<td>b</td>
<td>124.0</td>
<td>15.6</td>
<td>242.0</td>
</tr>
<tr>
<td>c</td>
<td>109.0</td>
<td>16.0</td>
<td>253.0</td>
</tr>
<tr>
<td>d</td>
<td>1.0</td>
<td>18.6</td>
<td>141.0</td>
</tr>
<tr>
<td>e</td>
<td>1.0</td>
<td>18.6</td>
<td>133.0</td>
</tr>
<tr>
<td>f</td>
<td>39.0</td>
<td>18.5</td>
<td>168.0</td>
</tr>
<tr>
<td>g</td>
<td>55.0</td>
<td>17.8</td>
<td>177.0</td>
</tr>
<tr>
<td>h</td>
<td>53.0</td>
<td>17.8</td>
<td>217.0</td>
</tr>
</tbody>
</table>
APPENDIX B. Flowchart, Description and Listing of EVAPMODL Program
FIGURE B1. Simplified Flowchart of EVAPMODL Program.
This program estimates evaporation from lakes by SIX METHODS, utilizing climatological data from a nearby land-based weather station.

The first is the method described in the article "An Aerodynamic formula to compute Evaporation from Open Water Surfaces" by G. Lakshman, 1972, J. Hydrol. 15: 209-225. This method requires measurements of water surface temperature as input data. However, in this model if water surface temperature is not available, average air temperature for the previous three consecutive time steps (hours or days) is used instead.

The second method follows the procedure described in the article "Climatological Estimates of Lake Evaporation" by F.I Morton, reported in the Journal of Water Resources Research, 1979, 15(1): 64-76. This is a simplified version where radiation is observed rather than calculated. This method is originally developed for monthly time step calculations, however in this model, Morton method is adapted for daily time step calculations.


The fourth is the Penman Lake method similar to method three above but with different wind function as explained in Hill (1992) CRPSM software and CRPSM user manual. This method uses both hourly and daily time step calculations.

The fifth is Priestley-Taylor (1972) method with new calibrated alpha coefficients of 1.30 for hourly data and 1.42 for daily data which were calibrated for Bear Lake conditions.

The sixth is Modified Penman Combination Equation (in one of the forms as in Businger (1956), Van Bavel (1966), or Monteith (1965)) in which the aerodynamic resistance term was adapted to lakes (zero surface resistance and smooth surface roughness length of momentum). This method uses both hourly and daily time step calculations.
The heat flux to or from the lake (Glake) is estimated using prediction equations as a function of net radiation over the lake. These prediction equations were developed for Bear Lake. However, when using this model for other lakes, these prediction equations should be evaluated and modified, if necessary, to adjust Glake term to reflect actual heat storage conditions in each particular lake.

This program allows using measured or remotely sensed estimated surface temperature (Tsurf) and net radiation (Rn) if available. However, in case of no or lack of actual measurements, net radiation is estimated by one of the following methods:

* Using surface Temperature, if available, to estimate the upward longwave radiation.

* Using calibrated equation (calibrated for Bear Lake) similar to Wright (1982) procedure which uses maximum and minimum air temperatures (for daily) or average temperature (for hourly) to estimate net longwave radiation.

In all the above net radiation methods, emissivity of the atmosphere is estimated following Idso (1981) equation, besides, cloudiness effect on downward longwave radiation is considered. Albedo of water is considered variable as the zenith angle of the sun changing in hourly basis, also, in seasonal basis as the surface characteristics changing (ice-water cycle).

In case of surface temperature is available, stability correction is considered whenever applicable (Aerodynamic-
Penman type equation and hourly time step calculation).

This program accepts weather data either in English units (CRPSM format) or Metric units (step by step program guided format), and also accepts either hourly or daily input data.

The outputs from this program are lake evaporation estimates using the above mentioned methods either as a rate in (W/m²) or as a depth in (mm/hr) or (mm/day) (evaporation estimates' outputs are shown both on screen and in output file called "*.LAK" where "*" represents the input filename without the extension. In addition, two other output files are created. The first file (*.INT) gives the associated intermediate calculations for checking purposes. The second file (*.LOG)
gives the lake evaporation estimates using both adapted Penman-Lake and Penman-Monteith methods along with aerodynamic resistance parameters associated with Penman-Monteith equation. In addition, in case of daily time step calculations; "*.LOG" output file gives the daily reference grass evapotranspiration estimate using Penman-Monteith equation for comparison purposes.

This program need some information about the lake location and elevation, wind and psychometric measurement heights, and lake area and perimeter. In case of no available information about the lake, Bear Lake information will be used (by default).

All the climatic parameters' calculations shown in the Climatic Parameters calculation segment of this program are following the procedures described in the ASCE Manual 70 (Jensen et al., 1990).

The following is listing of the EVAPMODL.BAS program along with all associated subroutines.

```basic
DECLARE SUB DOCUMENT (DOCS)
DECLARE SUB JDAY (SIDS, DA, MO, YR, JD!)
DECLARE SUB RACALC (JD!, TIME, RAI)
DECLARE SUB SATYAP (TI, esl)
DECLARE SUB STABILITY (Tws, WD, zom, zov, Reero)
DECLARE SUB ALBEDO (Tws, TX, JD, TIME, ALBED)
DECLARE SUB NETRAO (Rs, RA, ALBED, Tws, ed, TXk, TNk, Rn)
DECLARE SUB ETOgrass (WD, TX, HI, ed, RA, As, LEgrass)

COMMON SHARED LAT, LATr, XLONG, STLONG, Elevm, ZENITH
COMMON SHARED TYP, FORMATS, Tws$, PI, g, sgm, ZW, ZP, EMsurf
COMMON SHARED Tav, ROU, DELTA, GAMA, NDYR, JD, Rso, del, omega, E, br
COMMON SHARED T1, T2, T3, CLOUD1, CLOUD2

DIM SHARED MD(12)
DIM V(12)

FOR I = 1 TO 12: READ MD(I): NEXT I
'Days per Month
DATA 31,28,31,30,31,30,31,31,30,31,30,31

Z$ = "Y"
DO WHILE Z$ = "YES" OR Z$ = "Y"

SCREEN 0
VIEW PRINT 1 TO 25
COLOR 7, 1
CLS
PRINT :
PRINT SPC(25); "LAKE EVAPORATION MODEL"
PRINT SPC(25); "JUMAH AMAYREH, Dec. 1994"
PRINT SPC(17); "USU BIOLOGICAL & IRRIGATION ENGINEERING"```
PRINT : INPUT " Do you want to know some tips about this model (Y/N)? ", DOC$
DOCS = UCASES(DOCS)

IF DOCS = "Y" THEN
LOCATE 23, 2
PRINT " ***** HIT <ESC> KEY TO CONTINUE ***** ",
CALL DOCUMENT(DOCS)
ELSE
END IF
VIEW PRINT 5 TO 24
COLOR 0, 7
CLS
PRINT : INPUT " Enter name of the lake ", LAKE$
PRINT : INPUT " Enter surface area of the lake in square miles ", AREA
IF AREA = 0 THEN AREA = 110 'Area of Bear Lake
PRINT : INPUT " Enter perimeter of the lake in miles ", PERM
IF PERM = 0 THEN PERM = 50 'Perimeter of Bear Lake
COLOR 1
PRINT : PRINT " NOTE: AREA & PERIMETER ARE REQUIRED FOR LAKSHMAN METHOD ONLY"
COLOR 4, 7
PRINT : INPUT " Are you using CRPSM format in your input data file? (YES OR NO)? ", FORMAT$
FORMAT$ = UCASES(FORMAT$)
IF FORMAT$ = "YES" OR FORMAT$ = "Y" THEN
    PRINT : INPUT ; " Enter filename of weather data --> ", FLIN$
PRINT :
ELSE
COLOR 14, 11
CLS
PRINT "***********************************************************************
PRINT " FOR DAILY DATA:"
PRINT "=====================================================
PRINT "MONTH DAY YEAR Tmax Tmin RHmax RHmin WINDSPEED SOLAR RAD (SURF TEMP) (NET RAD)"
PRINT " # # # C C % % m/sec W/M2 C W/M2"
PRINT :
PRINT : PRINT " FOR HOURLY DATA:"
PRINT "=====================================================
PRINT "MONTH DAY TIME Tmax Tmin RHmax RHmin WINDSPEED SOLAR RAD (SURF TEMP) (NET RAD)"
PRINT " # # # C C % % m/sec W/M2 C W/M2"
PRINT :
COLOR 0, 7
PRINT " ***** HIT <RETURN> KEY TO CONTINUE ***** ",
SLEEP: INPUT DUMMY$
COLOR 1, 7
CLS
PRINT : PRINT " H IS HOURLY DATA ": PRINT " D IS DAILY DATA "
COLOR 4
The document contains a program written in BASIC, which seems to be a weather data collection program. The program prompts the user for various input variables such as the type of data, surface temperature, net radiation, filename, lake elevation, site latitude, lake longitude, wind speed measurement, and psychometric measurement. It then processes these inputs and stores them in variables for later use.

The program also includes logic to handle default values for certain inputs, such as if the input is not provided or if it is not within a valid range. It uses conditional statements, string manipulation functions, and file I/O operations to gather and store the data.
IF FORMAT$ = "YES" OR FORMAT$ = "N" THEN
TYPS$ = "MID"

FOR L = 1 TO 13
LINE INPUT #1, DUMMS$ 

IF L = 2 THEN 
ELEVft = VAL(MID$(DUMMS$, 29, 7)) 'Elevation of the site in ft
ELEVm = ELEVft * .3048 'convert to meters
LAT = VAL(MID$(DUMMS$, 36, 10)) * .01 'Latitude of the site in deg.
XLONG = VAL(MID$(DUMMS$, 46, 10)) 'Longitude of site in deg.
END IF

IF L = 9 THEN WHT = VAL(MID$(DUMMS$, 40, 5)) 'Wind speed height in meter
IF L = 13 THEN SKP = VAL(MID$(DUMMS$, 2, 2)) 'To Skip name of the station

NEXT L
END IF

'************** CONSTANTS: ***************

CONVERT = 24 * 60 / (.69758 * 1000) 'To convert from W/m2 to la/day
CONVERT = 2.064279366

G = -9.8 'gravity acceleration m/sec^2
PI = 22 / 7
Po = 101.3 'atmospheric pressure at sea level kpa
EMMsurf = .97 'emissivity of the water surface
σm = 5.67E-08 'Stefan-Boltzmann constant, W.m^-2 / K^-4

eO = 6.11 'mb, saturation vapor pressure at 0 degrees C

LATr = LAT * PI / 180 'site latitude in radian

STLONG = INT(XLONG / 15) * 15 'standard longitude for site in deg.

TWS1 = 10: TWS2 = 10: TWS3 = 10 'initial value for Lakshman method
T1 = 10: T2 = 10: T3 = 10 'initial values for Grass
CLOUD1 = 1: CLOUD2 = 1 'initial values for night cloud

SUMmoron = 0: SUMkhr = 0: SUMlaksh = 0 'initial values to determine total
SUMPLLK = 0: SUMprsT = 0: SUMMPN = 0 'evaporation for each method

'************ OUTPUT FORMAT: *************

F1$ = "\ "
F2$ = "\ 
F3$ = "\ 
F4$ = "\ 
F5$ = "\ 
F6$ = "\ 
F7$ = "\ 
F8$ = "\ 

VIEW PRINT 1 TO 25

CLS

PRINT #2, "THE SITE IS: ", LAKENAMES$
PRINT #3, "THE SITE IS: ", LAKENAMES$
PRINT #4, "THE SITE IS: ", LAKENAMES$

PRINT #2, "DATA FILE IS: ", FLINS$
PRINT #3, "DATA FILE IS: ", FLINS$
PRINT #4, "DATA FILE IS: ", FLINS$

PRINT #2, "THE SITE IS: ", LAKENAMES$
PRINT #3, "THE SITE IS: ", LAKENAMES$
PRINT #4, "THE SITE IS: ", LAKENAMES$

PRINT #2, "DATA FILE IS: ", FLINS$
PRINT #3, "DATA FILE IS: ", FLINS$
PRINT #4, "DATA FILE IS: ", FLINS$
PRINT : PRINT #2, : PRINT #3, : PRINT #4,
IF UNITS = "D" THEN
IF TYP$ = "H" THEN
PRINT , " LAKE EVAPORATION (mm/hr)"
PRINT #2, " LAKE EVAPORATION (mm/hr)"
ELSE
PRINT , " LAKE EVAPORATION (mm/day)"
PRINT #2, " LAKE EVAPORATION (mm/day)"
ENDIF
ELSE
PRINT , " LAKE EVAPORATION (W/M2)"
PRINT #2, " LAKE EVAPORATION (W/M2)"
ENDIF
PRINT #2,
IF TYP$ = "H" THEN
PRINT , " SITE MO DA TIME LAKSHMAN PNMLAK PRS-TYL R PN-MONTH" 
PRINT , " SITE MO DA TIME LAKSHMAN PNMLAK PRS-TYL R PN-MONTH" 
PRINT #2, " SITE MO DA TIME LAKSHMAN PNMLAK PRS-TYL R PN-MONTH"
PRINT #2, " ------------------------------- 
ELSE
PRINT , " SITE DATE MORTON KOHLER LAKSHMN PNMLAK PRS-TYL R PN-MONTH" 
PRINT , " SITE DATE MORTON KOHLER LAKSHMN PNMLAK PRS-TYL R PN-MONTH" 
PRINT #2, " SITE DATE MORTON KOHLER LAKSHMN PNMLAK PRS-TYL R PN-MONTH"
PRINT #2, " ------------------------------- 
ENDIF
IF TYES = "H" THEN
PRINT #3, " HOURLY EVAPORATION AVERAGES"
PRINT #3, " "
PRINT #3, " "
PRINT #3, " PNMLAK ------- P_N_M_M_O_N "
PRINT #3, " PRINT #3, " (nm) EVAP zom zov re "
PRINT #3, " (mm) (mm) (mm) (s/m)"
PRINT #3, " PRINT #3, " JD TIME "
PRINT #3, " "
ELSE
PRINT #3, " DAILY EVAPORATION AVERAGES"
PRINT #3, " "
PRINT #3, " GRASS PNMLAK ------- P_N_M_M_O_N "
PRINT #3, " PRINT #3, " (nm) (nm) EVAP zom zov re "
PRINT #3, " (mm) (mm) (mm) (s/m)"
PRINT #3, " PRINT #3, " JD "
PRINT #3, " "
ENDIF
IF TYP$ = "H" THEN
PRINT #4, " PARAMETER AVERAGES"
PRINT #4, 
PRINT #4,
PRINT #4, "TIME JD ALBEDO RA Rso Rn Glake ea ed LAMDA DELTA GAMA"
PRINT #4, ";<--- W/M2 ---> < kpa-> (MJ/kg) <--- kpa/c-->
PRINT #4, 
ELSE
PRINT #4, "PARAMETER AVERAGES"
PRINT #4, 
PRINT #4, " JD ALBEDO RA Rso Rn Glake ea ed LAMDA DELTA GAMA"
PRINT #4, "<--- W/M2 ---> < kpa-> (MJ/kg) <--- kpa/c-->
PRINT #4, 
END IF
COLOR 14, 3
VIEW PRINT 5 TO 22
CLS
DO WHILE NOT EOF(1)
IF TYP$ = "H" THEN
TYP = 24
ELSE
TYP = 1
END IF
IF FORMATS = "YES" OR FORMATS = "Y" THEN
SID$ = INPUT$(SKP, #1) 'The first SKP char's contain station ID and date
INPUT #1, V(1), V(2), V(3), V(4), V(5), V(6), V(7)
TX = (V(1) - 32) * 5 / 9 'convert from F to oC
TN = (V(2) - 32) * 5 / 9
RHX = V(3)
RHN = V(4)
PPT = V(5)
WND = V(6) * 1609 / 86400 ' convert from mi/day to m/sec
Rs = V(7) / CONVERT 'convert from Langley/day to W/M^2
TIME = 0
Tws$ = "NO"
Rn$ = "NO"
ELSE
IF Tws$ = "YES" OR Tws$ = "Y" THEN
IF Rn$ = "YES" OR Rn$ = "Y" THEN
INPUT #1, V(1), V(2), V(3), V(4), V(5), V(6), V(7), V(8), V(9), V(10), V(11)
Tws = V(10): Rn = V(11)
ELSE
INPUT #1, V(1), V(2), V(3), V(4), V(5), V(6), V(7), V(8), V(9), V(10)
Tws = V(10)
END IF
ELSE
IF Rn$ = "YES" OR Rn$ = "Y" THEN
INPUT #1, V(1), V(2), V(3), V(4), V(5), V(6), V(7), V(8), V(9), V(10)
ELSE

\[ Rn = V(10) \]

ELSE

INPUT #1, V(1), V(2), V(3), V(4), V(5), V(6), V(7), V(8), V(9)

END IF

END IF

IF TYP = 1 THEN

MO = V(1); DA = V(2); YR = V(3)
TX = V(4); TN = V(5); RHX = V(6)
RHN = V(7); WND = V(8); Rs = V(9)

TIME = 0
ELSE

MO = V(1); DA = V(2); TIME = V(3)
TX = V(4); TN = V(5); RHX = V(6)
RHN = V(7); WND = V(8); Rs = V(9)

END IF

END IF

IF V(1) = 0 AND V(2) = 0 AND V(6) = 0 THEN EXIT DO

********** Climatic Parameters calculations: **********

='Averages of Temperatures (c) and Relative Humidity (%)
Tav = (TX + TN) / 2
RHav = (RHX + RHN) / 2
TXk = TX + 273.16; TNk = TN + 273.16; Tavk = Tav + 273.16 ' convert to k

'Wind speed at 2 meter (m/sec)
U2 = WND * (2 / WHT) ^ (1 / 11.5) ' (1/11.5 = 0.087) is a wind coefficient resulted
' from Bear Lake study comparable to 0.2 coefficient
' normally used in agronomy applications (for Alfalfa)

CALL JDAY(SIDS, DA, MD, YR, JD)
CALL RACALC(JD, TIME, RA)
CALL ALBEDO(Tws, TX, JD, TIME, ALBED)
CALL SATVAP(Tav, eTav)
CALL SATVAP(TN, eTN)

\( ea = eTav \) 'Saturated vapor pressure (kpa)

IF TYP = 1 THEN
\( ed = .01 \times RHX \times eTN \) 'Actual vapor pressure (kpa)
ELSE
\( ed = .01 \times RHav \times eTav \)
END IF

IF FORMATS = "YES" OR FORMATS = "Y" THEN

CALL NETRAD(Rs, RA, ALBED, Tws, ed, TXk, TNk, Rn)
ELSE

IF Rn$ = "YES" OR Rn$ = "Y" THEN

Rn = Rn
ELSE
CALL NETRAD(Rs, RA, ALBED, Tws, ed, TXk, TNk, Rn)

END IF
END IF

'Atmospheric pressure at the site elevation (kpa)
P = Po * ((Tavk - (.0065 * ELEVm)) / Tavk) ^ (9.8 / (.0065 * 287))

' Virtual temperature (K)
Tkv = Tavk * (1 - .378 * ed / P) ^ -1

'Atmospheric density (kg/m3)
ROO = 3.486 * P / Tkv

'kinematic viscosity in (m^2/sec)
V = (1.33 + .00908 * Tav) / (987 * P)

'Latent Heat of Vaporization (MJ/kg)
LHvap = 2.501 - (.002361) * Tav

' Latent Heat of Sublimation (MJ/kg)
LHsub = LHvap * 1.15

'Slope of vapor pressure curve (kpa/c)
DELTA = 4098 * ea / (Tav + 237.3) ^ 2

'Psychometric constant (kpa/c)
GAMA = .00163 * P / LHvap

'heat flux to or from the lake (Glake) prediction equations
calibrated for Bear Lake (W/M2)

IF TYP = 1 THEN
Glake = -62 + .984 * Rn
ELSE
IF Rs > 5 THEN
Glake = -68.5 + .998 * Rn
ELSE
Glake = 7.82 + 1.2 * Rn - 22.564 * U2
END IF
END IF

****** Evaporation estimates ******
*************************************************************************
*************- The Lakshman method -*************
*************************************************************************

'Convert U2 from m/sec to mi/hr
U2mph = U2 * 3600 / 1609

'To find water surface Temperature
IF Tws$ = "YES" OR Tws$ = "Y" THEN
    Tws laksh = Tws
ELSE
TWS1 = TWS2; TWS2 = TWS3; TWS3 = Tav

In case of water surface temperature is not available, assume the
'temperature of the water surface equals to the average air temperature
' of the last 3 hours or days (depending on the time step used)

Twsllaksh = (TWS1 + TWS2 + TWS3) / 3

END IF

'To find vapor pressure of the water surface
CALL SATVAP(Twsllaksh, eTws)

'exponent of a power-type wind law
mn = 1 / 11.5

'The fetch distance over the water surface (ft)
X = 4 * AREA * (5280) ^ 2 / (PERM * (5280))

'Turbulent boundary thickness (cm)

dd = .078 * ((2 * mm + 1) * (mm + 1) / mm) ^ .8 * (V * 10000) ^ .2 * (mm + 1) ^ .6

dd = .01 * dd * (30.48 * X) ^ .8 * (U2mph) ^ -.2

'Mass transfer coefficient (in/(hr-mph-mb)
nn = .00039 * mm ^ .2 / ((mm + 1) ^ .6 * (2 * mm + 1) ^ .2)
n = nn * (dd / 2) ^ (1.8 * mm) * (PERM * (5280) / (AREA * (5280) ^ 2)) ^ .2

LElaksh = n * U2mph ^ .8 * (10 * (eTws - ed)) * 25.4 'mm/hr

IF ALBED > .5 THEN
LElaksh = LElaksh * LHsub * 1000000 / 3600!  'convert to W/m2
ELSE
LElaksh = LElaksh * LHvap * 1000000 / 3600!  'convert to W/m2
END IF

SUMlaksh = SUMlaksh + LElaksh

IF TYP = 24 THEN GOTO 100  'TO SKIP MORTON & KOHLER METHODS

******************************************************************************
******************************************************************************
******************************************************************************
******************************************************************************
******************************************************************************
******************************************************************************
******************************************************************************

'Ratio of atmospheric pressure at the lake to that at sea level
Pratio = P / Po

'Solar declination
th = 23.5 * COS(21 * PI * (JD - 1721) / 3651)
th1 = LAT - 89.999
th2 = LAT + 89.999
IF th < th1 THEN th = th1
IF th > th2 THEN th = th2
thR = th * PI / 180!  'convert to radian
OMGA is the radians the earth rotates between sunrise and noon
\[
\cos\text{OMGA} = -\tan(\text{LATr}) \times \tan(\text{thR})
\]
IF \(\cos\text{OMGA} < -1\) THEN \(\cos\text{OMGA} = -1\)
\[
\text{OMGA} = \frac{\pi}{2} - \arctan(\cos\text{OMGA}) / \sqrt{1 - \cos\text{OMGA}^2}
\]

\(Z\) is the average angular zenith distance of the sun
\[
\cos\text{Z} = \sin(\text{LATr}) \times \sin(\text{thR}) + \cos(\text{LATr}) \times \cos(\text{thR}) \times \sin(\text{OMGA}) / \text{OMGA}
\]

Compute min and max albedo
\[
\text{ABSsa} = \text{ABS}(\text{LATr} - \text{thR})
\]
\[
\text{al} = 0.04 \times (\exp(0.855) - (1.71 / \pi \times \cos(\text{ABSa}) + \sin(\text{ABSa}) \times \exp(0.0095 \times \text{ABSa})) / (1.296 \times (1 - \sin(\text{ABSa}))) ^ {0.19}
\]
IF \(\text{Tav} \geq 0\) THEN
\[
\text{aa} = 0
\]
ELSE
\[
\text{aa} = 0.6
\]
END IF
\[
\text{au} = \text{al} + \text{aa}
\]

Sunshine duration ratio
\[
\text{SS} = (\text{Rs} / \text{RA} - 0.18) / 0.55
\]
IF \(\text{SS} < 0\) THEN \(\text{SS} = 0\)
IF \(\text{SS} > 1\) THEN \(\text{SS} = 1\)

Cloud cover ratio
\[
\text{CC} = (1 - \text{SS}) \times 0.75
\]

Ratio of average to clear sky atmospheric radiation
\[
r = 1 + (0.25 - 0.005 \times (\text{eTA} - \text{eDEW})) \times \text{CC} \times 2
\]
IF \(r < 1\) THEN \(r = 1\)

Net longwave radiation loss
\[
\text{Rbb} = \text{EMMsurf} \times \text{sgm} \times (\text{Tav} + 273) \times 4 \times (1 - r \times (0.707 + \text{eDEW} / 158))
\]

Min net radiation
\[
\text{RWL} = (1 - \text{au}) \times \text{Rs} - \text{Rbb}
\]

Max net radiation
\[
\text{RIAJ} = (1 - \text{al}) \times \text{Rs} - \text{Rbb}
\]

Stability factor
\[
\text{Z} = (\text{ABS}(\text{eTA} - \text{eDEW}) / \text{eTO}) \times 0.12
\]
IF \(\text{Tav} \geq 0\) THEN
\[
\text{zfw} = 221 \text{ W/m}^2/\text{mb}
\]
\[
\text{gps} = 0.66 \text{ W/m}^2/\text{C}
\]
ELSE
\[
\text{zfw} = 221 \times 1.15 \text{ W/m}^2/\text{mb}
\]
\[
\text{gps} = 0.66 / 1.15 \text{ W/m}^2/\text{C}
\]
END IF

Relative humidity as a ratio (0 to 1)
\[
r = \text{eDEW} / \text{eTA}
\]

Vapor transfer coefficient
\[
\text{fw} = \text{zfw} / \text{Z}
\]

Heat transfer coefficient
\[
\text{L} = \text{gps} \times \text{Pratio} + 4! \times \text{EMMsurf} \times \text{sgm} \times (\text{Tav} + 273) \times 3 / \text{fw}
\]
\[
\text{d} = (1! \times \text{L} / \text{DELTA}) \times -1
\]
\[
\text{psi} = (1! \times \text{L} / \text{DELTA} \times (0.5 + 0.5 \times r + \text{L} / \text{DELTA}) / (r + \text{L} / \text{DELTA}) \times -1 + 0.26
\]

Advective energy, W/m^2
\[
\text{M} = 0.66 \times \text{Rbb} - 0.44 \times \text{RIAJ}
\]
IF \( M < 0 \) THEN \( M = 0 \)
\[
ee = \frac{fw \times (eT - eDEW)}{E1}
\]
\[
E1 = \frac{.7 \times \psi}{(1 - d) \times M + (\psi - d) \times (1 - d) \times RWL}
\]
IF \( ee < E1 \) THEN \( ee = E1 \)
\[
M1 = \frac{(1 - d) \times \psi}{ee} + (\psi - d) \times \psi \times RWL
\]
IF \( M > M1 \) THEN \( M = M1 \)

' Net radiation if the surface were at air temp., W/m^2

\[
RW = RW1
\]
\[
RW1 = \frac{(1 - d) \times \psi - \psi}{(psi - d) \times M}
\]
IF \( RW > RW1 \) THEN \( RW = RW1 \)

' Potential evaporation, W/m^2

\[
LEP = d \times RW + (1 - d) \times ee
\]

' Lake evaporation, W/m^2

\[
LEW = \psi \times (RW + M)
\]
\[
LEmorton = LEW
\]
\[
SUMmorton = SUMmorton + LEmorton
\]

/'Estimated lake psychrometric constant (mb/oc)

\[
Up = WND \times (86400 / 1609) \times (1 / 11.5)
\]
\[
GAMAl = .000661 \times P \times 10
\]
\[
C1khlr = 10 \times \delta \times (10 \times \delta - GAMA) \times (10 \times \delta - GAMA)
\]
\[
C2khlr = 1 - C1khlr
\]
\[
LEr&d = C1 \times (Rn - Glaeke)
\]
IF \( TYP = 1 \) THEN
\[
LEaPNLK = (1 / 3600) \times C2 \times (6.43) \times (1 + .53 \times U2) \times (ea \cdot ed)
\]
LEaPNLK = LEaPNLK * 1000000 / 24
ELSE
LEaPNLK = C2 * (6.43 / 24) * (1 + .53 * U2) * (ea - ed) / \(\text{W/M}^2\)
LEaPNLK = LEaPNLK * 1000000 / 3600
END IF

LEPNLK = .7 * (LErad + LEaPNLK) / \(\text{W/M}^2\)
SUMPNLK = SUMPNLK + LEPNLK

//*************************/Prestiley Taylor method**************************//
//*************************/Modified Penman Combination method**************************//

IF TYP = 24 THEN
ALPHA = 1.3
ELSE
ALPHA = 1.42
END IF

LEPrsT = ALPHA * LErad / \(\text{W/M}^2\)
SUMPrsT = SUMPrsT + LEPrsT

CD = .001 * (.75 + .067 * WND) / \(\text{wind Drag Coefficient calibrated for Bear Lake conditions}\)
uf = WND * CD ^ .5 / \(\text{friction velocity}\)
ZP = PHT
ZW = WHT
zom = .135 * V / uf / \(\text{for smooth surface}\)
zov = .395 * V / uf / \(\text{for smooth surface}\)
disp = 0 / \(\text{zero displacement for water}\)
K = .41 / \(\text{Von Karman's constant}\)
'to find the convective heat transfer coefficient (1/ra)
IF TYP = 24 THEN
IF Tws$ = "YES" OR Tws$ = "Y" THEN
CALL STABILITY(Tws, WND, zom, zov, Raero)
ralake = Raero
ELSE
ralake = LOG(ZW / zom) * LOG(ZP / zov) / (WND * K ^ 2)
END IF
ELSE
ralake = LOG(ZW / zom) * LOG(ZP / zov) / (WND * K ^ 2)
END IF
'to find lake evaporation

\[ C2MPN = \frac{1}{\Delta + \gamma} \]

\[ \text{LEaMPN} = C2MPN \times R\gamma \times 1013 \times (1 / \text{lake}) \times (ea - ed) \quad \text{W/M}^2 \]

\[ \text{LEMPN} = \text{LErad} + \text{LEaMPN} \quad \text{W/M}^2 \]

\[ \text{SUMMPN} = \text{SUMMPN} + \text{LEMPN} \]

IF TYP = 1 THEN CALL ETOgrass(WND, TX, TN, ed, RA, Rs, LEgrass)

\[ \text{SUMgrass} = \text{SUMgrass} + \text{LEgrass} \]

IF ALBED > .5 THEN

\[ \text{LAMDA} = \text{LHsub} \]

ELSE

\[ \text{LAMDA} = \text{LHvap} \]

END IF

zomm = zom * 1000
zovmm = zov * 1000

\[ \text{EPLNK} = \text{LEPNLK} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{EMPLN} = \text{LEMPN} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{TEgrass} = \text{LEgrass} \times 3600 \times 24 / (\text{LHvap} \times 1000000) \]

IF UNIT$ = "D" THEN

IF TYP = 1 THEN

\[ \text{LEMorton} = \text{LEmorton} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEKhlr} = \text{LEkhlr} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{LElaksh} = \text{LElaksh} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEPNLK} = \text{LEPNLK} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEPrsT} = \text{LEPrsT} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEMPN} = \text{LEMPN} \times 3600 \times 24 / (\text{LAMDA} \times 1000000) \]

ELSE

\[ \text{LElaksh} = \text{LElaksh} \times 3600 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEPNLK} = \text{LEPNLK} \times 3600 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEPrsT} = \text{LEPrsT} \times 3600 / (\text{LAMDA} \times 1000000) \]

\[ \text{LEMPN} = \text{LEMPN} \times 3600 / (\text{LAMDA} \times 1000000) \]

END IF

ELSE

END IF

IF TYP = 24 THEN

PRINT USING F3$; FLOUT1$; V(1); V(2); V(3); LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #2, USING F3$; FLOUT1$; V(1); V(2); V(3); LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #3, USING F4$; JD; TIME; EPNLK; EM PN; zonmm; zovmm; ralake
PRINT #4, USING F6$; TIME; JD; ALBED; RA; Rso; Rn; Glake; ea; ed; LAMDA; DELTA; GAMA
ELSE
IF FORMATS = "YES" OR FORMATS = "Y" THEN
PRINT USING F2$; SIDS; LEmorton; LEkhlr; LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #2, USING F2$; SIDS; LEmorton; LEkhlr; LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #3, USING F4$; JD; TEgrass; EPNLK; EMPN; zonmm; zovmm; ralake
PRINT #4, USING F5$; JD; ALBED; RA; Rso; Rn; Glake; ea; ed; LAMDA; DELTA; GAMA
ELSE
PRINT USING F1$; FLOUT1$; V(1); V(2); V(3); LEmorton; LEkhlr; LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #3, USING F1$; FLOUT1$; V(1); V(2); V(3); LEmorton; LEkhlr; LElaksh; LEPNLK; LEPrsT; LEMPN
PRINT #4, USING F4$; JD; TD; RA; Rso; Rn; Glake; ea; ed; LAMDA; DELTA; GAMA
END IF
END IF
LOOP
IF TYP = 1 THEN
SUMmorton = SUMmorton * 3600 * 24 / (LAMDA * 1000000)
SUMkhlr = SUMkhlr * 3600 * 24 / (LAMDA * 1000000)
SUMlaksh = SUMlaksh * 3600 * 24 / (LAMDA * 1000000)
SUMPNLK = SUMPNLK * 3600 * 24 / (LAMDA * 1000000)
SUMPrsT = SUMPrsT * 3600 * 24 / (LAMDA * 1000000)
SUMMPN = SUMMPN * 3600 * 24 / (LAMDA * 1000000)
ELSE
SUMlaksh = SUMlaksh * 3600 / (LAMDA * 1000000)
SUMPNLK = SUMPNLK * 3600 / (LAMDA * 1000000)
SUMPrsT = SUMPrsT * 3600 / (LAMDA * 1000000)
SUMMPN = SUMMPN * 3600 / (LAMDA * 1000000)
END IF
PRINT : COLOR 0
IF TYP$ = "H" THEN
PRINT USING F7$; " TOTALS (nm) : "; SUMlaksh; SUMPNLK; SUMPrsT; SUMMPN
PRINT #2, USING F7$; " TOTALS (nm) : "; SUMlaksh; SUMPNLK; SUMPrsT; SUMMPN
ELSE
PRINT USING F8$; " TOTALS (mm): "; SUMmorton; SUMkhlr; SUMlaksh; SUMPNLK; SUMPrsT; SUMMPN
PRINT #2, USING F8$; " TOTALS (mm): "; SUMmorton; SUMkhlr; SUMlaksh; SUMPNLK; SUMPrsT; SUMMPN
END IF
CLOSE (1)
CLOSE (2)
CLOSE (3)
CLOSE (4)
COLOR 1, 7
PRINT : PRINT : INPUT "Would you like to run another file? (Y/N) --- > ", Z$ Z$ = UCASES(Z$)
LOOP
END
SUB ALBEDO (Tws, TX, JD, TIME, ALBED)

IF TYP = 1 THEN
   ALBED = .055
ELSE
   SolarNoon = 12 - (4 * (STLONG - XLONG) + E) / 60
   XX = (SIN(del) * SIN(LATr) + COS(del) * COS(LATr) * COS(omega))
   ZENITH = ABS(ATN(XX / SQRT(-XX * XX + 1)) + 1.5707963)
   IF ZENITH >= PI / 2 THEN ZENITH = 1.57
   ALBED = .045 + .12 * EXP(-.08 * (90 - (ZENITH * 180 / PI)))
END IF
IF Tws$ = "YES" OR Tws$ = "Y" THEN
   IF TX <= 0 THEN ALBED = ALBED + .85
ELSE
   IF TX <= 0 THEN ALBED = ALBED + .85
END IF
END SUB

SUB DOCUMENT (DOCS)
VIEW PRINT 6 TO 22
COLOR 1, 11
CLS
PRINT :
PRINT "This program estimates evaporation from lakes by SIX"
PRINT "METHODS, utilizing climatological data from a nearby land-";
PRINT "based weather station."
COLOR 14
PRINT :
PRINT "The first is the method described in the article 'An"
PRINT "Aerodynamic formula to compute Evaporation from Open Water";
PRINT "Surfaces' by G. Lakshman, 1972, J. Hydrol. 15: 209-225. This"
PRINT "method requires measurements of water surface temperature"
PRINT "as input data. However, in this model if water surface"
PRINT "temperature is not available, average air temperature for"
PRINT "the previous three consecutive time steps (hours or days) is"
PRINT "used instead."
SLEEP
CLS
PRINT :
PRINT "The second method follows the procedure described in the"
PRINT "article 'Climatological Estimates of Lake Evaporation' by"
PRINT "F.I Horton, reported in the journal of Water Resources"
PRINT "Research 15(1): 64-76. This is a simplified version where"
radiation is observed rather than calculated. This method is originally developed for monthly time step calculations, however in this model, Morton method is adapted for daily time step calculations.

The third is the method proposed by Kohler, Nordenson, and Fox, in the Research Paper No. 38, 'Evaporation from Pans and Lakes', 1955, U.S. Department of Commerce, Weather Bureau. This method uses daily time step calculations only.

The fourth is the Penman Lake method similar to methods three and four, with different wind function as explained in Hill (1992) CRPSM software and CRPSM user manual. This method uses both hourly and daily time step calculations.

The fifth is Prestiley Taylor (1972) method with new calibrated alpha coefficients of 1.30 for hourly data and 1.42 for daily data which were calibrated for Bear Lake conditions.

The sixth is Modified Penman Combination Equation (in one of the forms as in Businger (1956), Van Bavel (1966), or Penman-Monteith (1965)) in which the aerodynamic resistance term was adapted to lakes (zero surface resistance and smooth surface roughness length of momentum). This method uses both hourly and daily time step calculations.

The heat flux to or from the lake (Glake) is estimated using prediction equations as a function of net radiation over the lake. These prediction equations were developed for Bear Lake. However, when using this model for other lakes, these prediction equations should be evaluated and modified, if necessary, to adjust Glake term to reflect actual heat storage conditions in each particular lake.

This program allows using measured or remotely sensed estimated surface temperature (Tsrf) and net radiation (Rn) if available. However, in case of no or lack of actual measurements, net radiation is estimated by one of the following methods:

* Using surface temperature, if available, to estimate the upward longwave radiation.
* Using calibrated equation (calibrated for Bear Lake) similar to Wright (1982) procedure which uses maximum and minimum air temperatures (for daily) or average temperature (for hourly) to estimate net longwave radiation.

In all the above net radiation methods, emissivity of the atmosphere is estimated following Idso (1981) equation, besides, cloudiness effect on downward longwave radiation is considered. Albedo of water is considered variable as the zenith angle of the sun changing in hourly basis, also, in seasonal basis as the surface characteristics changing.
PRINT "In case of surface temperature is available, stability"
PRINT "correction is considered whenever applicable (Aerodynamic-"
PRINT "Penman type equation and hourly time step calculation)."
PRINT :
PRINT "This program accepts weather data either in English units"
PRINT "(CRPSM format) or Metric units (step by step program guided"
PRINT "format), and also accepts either hourly or daily input data."
SLEEP
COLOR 14, 11
CLS
PRINT :
PRINT "The outputs from this program are lake evaporation estimates"
PRINT "using the above mentioned methods either as a rate in (W/m2)"
PRINT "or as a depth in (mm/hr) or (mm/day) (evaporation estimates"
PRINT "outputs are shown both on screen and in output file called"
PRINT "*.LAK' where '*' represents the input filename without the"
PRINT "extension). Two other output files are created:"n
PRINT "The first file (*.INT) gives the associated intermediate"
PRINT "calculations for checking purposes."
PRINT "The second file (*.LOG) gives the lake evaporation estimates"
PRINT "using both adapted Penman-Lake and Penman-Monteith methods"
PRINT "along with aerodynamic resistance parameters associated with"
PRINT "Penman Monteith equation."
PRINT "In case of daily time step calculations; '*.LOG' output file"
PRINT "gives the daily reference grass evapotranspiration estimate"
PRINT "using Penman-Monteith equation for comparison purposes."
SLEEP
COLOR 0
CLS
PRINT :
PRINT : PRINT : PRINT : PRINT :
PRINT "This program need some information about the lake location"
PRINT "and elevation, wind and psychometric measurement heights,"
PRINT "and lake area and perimeter. In case of no available"
PRINT "information about the lake, Bear Lake information will be"
PRINT "used (by default)."
PRINT :
SLEEP
END SUB

*******************************************************************************
*******************************************************************************
SUB ETOgrass (WND, TX, TH, ed, RA, Rs, LEgrass)

hc = .12  'grass height (m)
dgrs = 2 * hc / 3  'zero plane displacement (m)
zomgrs = .125 * hc  'roughness length of momentum (m)
zohgrs = .1 * zom  'roughness length of heat and water vapor (m)
U2grass = WND * LOG((2 - dgrs) / zomgrs) / LOG((ZW - dgrs) / zomgrs)
RGrass = 70  'crop resistance sec/m
RAGrass = 208 / U2grass  'aerodynamic resistance sec/m

'To find net radiation for grass Rngrass
Rso = .75 * RA
ALBEDgrs = .29 + .06 * SIN((JD + 96) / 57.3)
RNS = (1 - ALBEDgrs) * Rs
a1grs = .26 + .1 * EXP(-((.0154 * (JD - 180)) ^ 2))
IF Rs / Rso > .7 THEN
   agrs = 1.126
bgrs = -.07
ELSE
   agrs = 1.017
   bgrs = -.06
END IF
FF = agrs * Rs / Rso + bgrs

BRNT = (a1grs • .139 * SQRT(ed)) * (((TX + 273.16) ^ 4 + (TN + 273.16) ^ 4) / 2)

RNL = sgm * FF * BRNT
Rngrass = RNS - RNL

TBAR = (T1 + T2 + T3) / 3
T1 = T2
T2 = T3
T3 = Tav

Ggrass = .38 * (Tav - TBAR) / 3600 ' MJ/M2/hr
Ggrass = Ggrass * 1000000 / 24 ' W/M2

CALL SATVAP(TX, etX)
CALL SATVAP(TN, etN)
eaa = (etX + etN) / 2

GAMASTAR = GAMA * (1 + RCgrass / RAGrass)
LEradgrass = DELTA * (Rngrass - Ggrass) / (DELTA + GAMASTAR)
LEaggrass = ROO * 1013 * (1 / RAGrass) * (eaa - ed) / (DELTA + GAMASTAR)
LEgrass = LEradgrass + LEaggrass

END SUB

*******************************************************************************

*******************************************************************************

SUB JDAY (SIDS, DA, MO, YR, JD)
' Calculates the Julian day

IF FORMATS = "YES" OR FORMATS = "Y" THEN
   MO = VAL(MID$(SID$, LEN(SID$) - 5, 2))
   DA = VAL(MID$(SID$, LEN(SID$) - 3, 2))
   YR = VAL(MID$(SID$, LEN(SID$) - 1, 2))
ELSE
   MO = MO
   DA = DA
   YR = YR
END IF

IF (YR / 4) - INT(YR / 4) = 0 THEN
   MD(2) = 29
   NDYR = 366
ELSE
   NDYR = 365
END IF

SUM = 0: J = 1
DO WHILE J <= 12 AND J <> MO
SUM = SUM + MD(J)
J = J + 1
LOOP

JD = DA + SUM
END SUB

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;; NET RADIATION SUBROUTINE ;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
';
SUB NETRAD (Rs, RA, ALBED, Tws, ed, TXk, TNk, Rn)

********* TO FIND CLOUDINESS EFFECT *********

IF RA <= 5 THEN
Rso = 0
CLOUD = (CLOUD1 + CLOUD2) / 2
ELSE
IF TYP = 1 THEN
Rso = .75 * RA
Ratio = Rs / Rso
IF Ratio > .7 THEN
   ac = .35
   bc = .65
ELSE
   ac = .65
   bc = .35
END IF
ELSE
ro = .97
r1 = .99
rk = 1.02
ao = (.4237 - .00821 * (6 - ELEVm / 1000) ^ 2) * ro
a1 = (.5055 + .00595 * (6.5 - ELEVm / 1000) ^ 2) * r1
KK = (.2711 + .01858 * (2.5 - ELEVm / 1000) ^ 2) * rk
TOUb = ao + a1 * EXP(-(KK / COS(ZENITH)))
TOUd = .271 - .2939 * TOUb
Rsoh = (TOUb + TOUd) * RA
Rso = Rsoh
Ratio = Rs / Rsoh
IF Ratio > .7 THEN
   ac = .35
   bc = .65
ELSE
   ac = .65
   bc = .35
END IF
END IF

CLOUD = (ac * Ratio + bc)
CLOUD1 = CLOUD2; CLOUD2 = CLOUD
END IF
IF Tws$ = "YES" OR Tws$ = "Y" THEN

EMMatm = .64 + .000595 * ed * EXP(1500 / (Tav + 273.16)) 'following Idso (1981)
'case 1: if water surface temperature is available:
LWatm = EMMatm * sgm * (Tav + 273.16) ^ 4
LWs surf = EMMsurf * sgm * (Tws + 273.16) ^ 4
Rn = (1 - ALBED) * Rs + CLOUD * (LWatm - LWsurf) 'W/M2
ELSE
'case 2: if water surface temperature is not available:
IF TYP = 24 THEN
IF JD < 150 OR JD > 235 THEN
a1 = .385 + .1 * EXP(-(.0154 * (JD - 180)) ^ 2)
b1 = -.12
ELSE
a1 = .26 + .1 * EXP(-(.0154 * (JD - 180)) ^ 2)
b1 = -.12
END IF
Rbo = sgm * (a1 + b1 * ed ^ .5) * (Tav + 273.16) ^ 4
ELSE
IF JD < 150 OR JD > 235 THEN
a1 = .38 + .1 * EXP(-(.0154 * (JD - 180)) ^ 2)
b1 = -.12
ELSE
a1 = .3 + .1 * EXP(-(.0154 * (JD - 180)) ^ 2)
b1 = -.12
END IF
Rbo = sgm * (a1 + b1 * ed ^ .5) * ((TXk ^ 4 + TNk ^ 4) / 2)
END IF
Rb = Rbo * CLOUD
Rn = (1 - ALBED) * Rs - .97 * Rb
END IF

END SUB

*******************************************************************************
*** EXTRATERRESTRIAL INCOMING SOLAR RADIATION SUBROUTINE ***
*******************************************************************************
SUB RACALC (JD, TIME, RA)
'Global solar constant (J/M2/sec OR W/M2)
Gsc = 1367 'Gsc=1.959 cal/cm2/min = 0.08202 MJ/M2/min
phi = LATr
dr = 1 + .033 * COS(2 * PI * JD / NDYR)
del = .4093 * SIN(2 * PI * (284 + JD) / NDYR)

' omegas=ACOS(-TAN(phi)*TAN(del))

ARGUM = -TAN(phi) * TAN(del)

omegas = PI / 2 - ATN(ARGUM / SQR(1 - ARGUM ^ 2))

IF omegas > 2 THEN omegas = 2
IF omegas < -1 THEN omegas = TAN(phi) * TAN(del) - 2

' *** Calculates the daily Ra for the site latitude (W/M2) ***

IF TYP = 1 THEN
RA = (1 / PI) * Gsc * dr * (omegas * SIN(phi) * SIN(del) + COS(phi) * COS(del) * SIN(omegas))
ELSE

' *** Calculates the hourly Ra for the site latitude (W/M2) ***

br = 2 * PI * (JD - 81) / 364
E = .1645 * SIN(2 * br) - .1255 * COS(br) - .025 * SIN(br)

h = ABS(TIME - .5)

omega = ((h + .06667 * (STLONG - XLONG) + E) - 12) * (PI / 12)

omega1 = omega - PI / 24
omega2 = omega + PI / 24

IF omega1 < -1 * omegas THEN omega1 = -1 * omegas
IF omega1 > omegas THEN omega1 = omegas

IF omega2 < -1 * omegas THEN omega2 = -1 * omegas
IF omega2 > omegas THEN omega2 = omegas

Rah = (12 / PI) * Gsc * dr * (COS(LATr) * COS(del) * (SIN(omega2) - SIN(omega1)) + (omega2 - omega1) * SIN(LATr) * SIN(del))

RA = Rah

END IF

END SUB

'**********************************************
'***** SATURATION VAPOR PRESSURE SUBROUTINE *****
'**********************************************

SUB SATVAP (T, es)

' Calculates the saturation vapor pressure (es) in kpa at a given temperature (TEMP).

IF Tav >= 0 THEN
a = 17.27
b = 237.3
ELSE
a = 21.88
b = 265.5
END IF
APPENDIX C. Data Analysis Results
TABLE C1. Wright (1982) Empirical Coefficients Calibrated for Kimberly, Idaho to be used with Eq. (35) for Alfalfa or Grass reference crops.

\[ a_i = 0.26 + 0.1e^{-0.0154(JD-180)^2} \quad (JD \text{ is day of the year}) \]

\[ b_i = -0.139 \quad \text{(for } e_d \text{ in kpa}) \]

For \( R_{sl}/R_{so} > 0.7 \)

\[ a = 1.126 \quad b = -0.07 \]

For \( R_{sl}/R_{so} < 0.7 \)

\[ a = 1.017 \quad b = -0.06 \]

TABLE C2. Coefficient of Determination of Parameters entered as Independent Variables to Estimate the Heat Flux into the Lake \( G_i \) (as the Dependent Variable).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient of Determination ( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daytime</td>
</tr>
<tr>
<td>( R_n ) (Net Radiation)</td>
<td>0.983</td>
</tr>
<tr>
<td>( u ) (Wind Speed)</td>
<td>-0.216</td>
</tr>
<tr>
<td>( T_s ) (Surface Temp.)</td>
<td>0.069</td>
</tr>
<tr>
<td>( T ) (Air Temp.)</td>
<td>0.047</td>
</tr>
<tr>
<td>( RH ) (Rel. Humid.)</td>
<td>-0.200</td>
</tr>
</tbody>
</table>
FIGURE C1. Comparison Between Emissivity of the Atmosphere Calculated by Residual (Eq. 48) and Estimated From Eq. (49).
FIGURE C2. Comparison of Residual and Estimated (Using Eq. 54) Heat Flux to the Lake.
FIGURE C3. Comparison Between BR Measured From BR System and (H/LE) Ratio Measured From EC System versus Time.
FIGURE C5. Comparison of over Lake and Lifton Station Measurements of Minimum and Maximum Daily Temperature and Relative Humidity of the Air.
FIGURE C6. Daily Comparison of over Lake and Lifton Station Measurements of Wind Speed and Solar Radiation.
Appendix D. Yearly Lake Energy Budget Study
In an attempt to estimate the yearly energy budget over the lake, nearby land-based weather data from Lifton station (since it mostly reflects over-lake conditions) were used in this analysis. Daily weather data for the years of 1993 and 1994 were available. Since wind speeds from Lifton station were about 70% lower than over-lake wind speed (see Fig. C6 in Appendix C), wind speed from Lifton station was adjusted by multiplying by a factor of 1.7. Daily latent Heat flux from the lake was estimated from Penman-Monteith equation \((LE_{p-M})\) using EVAPMODL program. Then, sensible heat flux from the lake was estimated by residual as:

\[
H_{res} = R_n - G_{lp} - LE_{p-M}
\]

where \(H_{res}\) is the sensible heat flux calculated by residuals, \(R_n\) is net radiation estimated from Eq. (35) using the new empirical coefficients calibrated for Bear Lake Eqs. (52-53), \(G_{lp}\) is heat flux into the lake estimated from the prediction equation calibrated for Bear Lake Eq. (58), and \(LE_{p-M}\) is latent heat flux from Penman-Monteith equation for lakes.

Comparison between \(LE_{p-M}\) and \(H_{res}\) versus time for the year 1994 is shown in Fig. D1. This figure shows that while the sensible heat flux from the lake was small during summer months, it was high during winter months. This
result means that the lake was loosing heat in the form of sensible heat as well as latent heat. This result may explain how the stored heat in the lake during summer months was released mostly as sensible and latent heat fluxes.

Also to compare the energy budget over the lake in monthly basis, Fig. D2 is presented. In this plot LEp-H, Hres, Rn, and Gp are the monthly averages based on daily estimates for the years 1993 and 1994 using Lifton station weather data. Moreover, to check the accuracy of both Gp and Hres, water Temperature profile in the deepest point of the lake (30 to 55 m) was most helpful even though the measurements were every about 4 weeks (8 to 12 weeks during winter months). The heat flux into the lake based on temperature profile (Gprofitle) was estimated similar to Eqs. (54-55) (assuming Gp=0). The sensible heat flux from the lake was estimated as:

\[
H_{\text{temp}} = \rho \ C_p \ \frac{T_s - T_a}{r_a}
\]  

(D2)

where \( H_{\text{temp}} \) is the sensible heat flux from the lake estimated from temperature gradient, \( \rho \) is the air density, \( C_p \) is the air specific heat at constant pressure, and \( r_a \) is the aerodynamic resistance for sensible heat transfer.
Monthly $r_a$ was estimated as the average of daily $r_a$ values in the corresponding month. Daily values of $r_a$ were estimated from Eq. (24) using $z_{om}$ for lakes as given by Eq. (39) and wind speed from Lifton station (after multiplying by a factor of 1.7). For both years (1993-1994) Fig. D2 shows the good agreement between $H_{res}$ and $H_{temp}$ with almost the same rates. However, there was some variations when comparing $G_{lp}$ and $G_{profile}$ especially during winter months. Even though $G_{profile}$ during winter months was estimated every 2 to 3 months, these variations may suggest that $G_{lp}$ equations were not suitable during winter months, or the net radiation was overestimated (it should be more negative) during winter months (i.e empirical coefficients given by Eqs. 52-53 were not suitable during winter months).

To clarify the energy balance over Bear Lake in monthly and yearly cycle, Table D1 is presented to summarize the energy components in 1993. In this table, the sensible heat was estimated from Eq. (D2) rather than by residuals (Eq. D1). Also, the last column of Table D1 is the summation of $G_{lp}$, $LE_{p-H}$, and $H_{temp}$ which was added to compare it with calculated $R_n$ (first column). Even though Table D1 show some deviations between calculated $R_n$ (first column) and residual $R_n$ (last column) in monthly basis, however, the annual averages are quite similar.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>Rn (W/m²)</th>
<th>Glp (W/m²)</th>
<th>LEp-m (W/m²)</th>
<th>Htemp (W/m²)</th>
<th>(G + LE + Htemp) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>-34.3</td>
<td>-95.6</td>
<td>21.7</td>
<td>23.0</td>
<td>-50.9</td>
</tr>
<tr>
<td>FEB</td>
<td>-60.8</td>
<td>-121.8</td>
<td>20.3</td>
<td>22.8</td>
<td>-78.7</td>
</tr>
<tr>
<td>MAR</td>
<td>25.5</td>
<td>-37.1</td>
<td>34.3</td>
<td>10.8</td>
<td>8.1</td>
</tr>
<tr>
<td>APR</td>
<td>124.5</td>
<td>60.5</td>
<td>46.8</td>
<td>6.0</td>
<td>113.3</td>
</tr>
<tr>
<td>MAY</td>
<td>166.3</td>
<td>101.7</td>
<td>61.5</td>
<td>-8.0</td>
<td>155.2</td>
</tr>
<tr>
<td>JUN</td>
<td>193.1</td>
<td>128.1</td>
<td>60.9</td>
<td>5.0</td>
<td>194.0</td>
</tr>
<tr>
<td>JUL</td>
<td>193.2</td>
<td>128.2</td>
<td>64.0</td>
<td>13.3</td>
<td>205.5</td>
</tr>
<tr>
<td>AUG</td>
<td>171.1</td>
<td>106.4</td>
<td>64.0</td>
<td>14.0</td>
<td>184.5</td>
</tr>
<tr>
<td>SEP</td>
<td>96.2</td>
<td>32.6</td>
<td>58.4</td>
<td>10.9</td>
<td>101.9</td>
</tr>
<tr>
<td>OCT</td>
<td>39.7</td>
<td>-23.0</td>
<td>58.4</td>
<td>10.5</td>
<td>45.9</td>
</tr>
<tr>
<td>NOV</td>
<td>9.5</td>
<td>-52.6</td>
<td>39.2</td>
<td>42.9</td>
<td>29.4</td>
</tr>
<tr>
<td>DEC</td>
<td>-4.9</td>
<td>-66.8</td>
<td>31.3</td>
<td>37.5</td>
<td>2.0</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>76.6</td>
<td>13.4</td>
<td>46.7</td>
<td>15.7</td>
<td>75.9</td>
</tr>
</tbody>
</table>
The results presented in both Fig. D2 and Table D1 show clearly how the heat storage in the lake plays a vital role in controlling the evaporation mechanism from Bear Lake. Also, the results show, in monthly basis, how the energy was absorbed and stored in the lake during summer months (leaving small energy portion for both latent and sensible heat fluxes), and how it was released in forms of sensible and latent heat fluxes and outgoing longwave radiation (negative $R_n$) during winter months. This simple energy budget study may help understanding the evaporation mechanism over the lake in a yearly cycle.
VITA

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