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THE FOLLOWING IS A MINOR REVISION OF THE PAPER "WATER TEMPERATURE MODELING: A PRACTICAL GUIDE" BY PETER SHANAHAN WHICH ORIGINALLY WAS PUBLISHED IN THESE PROCEEDINGS. REVISIONS UPDATE COMPUTE CODES APPEARING IN TABLES 4 AND 5 OF THE PAPER.

WATER TEMPERATURE MODELING: A PRACTICAL GUIDE

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ABSTRACT

This paper is a review of techniques for the computation of water temperature in surface water bodies. Emphasis is placed on the practical aspects of applying water temperature models. The discussion focuses particularly upon the problems of obtaining and adapting the meteorological data required as input for surface heat transfer calculations.

INTRODUCTION

Computations of water temperature are employed to determine the environmental impacts of thermal discharges, to evaluate the performance of cooling ponds used to dispose of waste heat from power plants, or to evaluate the hydrothermal characteristics of water bodies in general. They are an essential part of the design of waste heat disposal structures and systems, and in the assessment of environmental effects of waste heat disposal.

The calculation of the water temperature of a surface-water body is based upon a heat balance similar to the water or mass balances employed in water quality modeling. The heat balance determines the change in the heat stored as equal to the influx of heat less the outflux of heat. The heat stored in a quantity of water is manifested by its temperature according to the following proportionality:

$$H = V \mathbf{r} c_p T \quad (1)$$

where

H	is the total heat content of the volume of water (Btu),
V	is the volume of water (ft ³),
r	is the density of water (lb/ft ³),
c _p	is the specific heat of water (Btu/lb/°F), and
T	is the water temperature (°F).

The fluxes of heat to or from a water body may be classified as follows:

1. Inflowing and outflowing water. These represent heat fluxes by virtue of their temperature. The calculation of these fluxes is a straightforward extension of Equation 1.
2. Heat conduction to or from the earth through the bottom of the water body. This is a minor component of the heat balance that is usually neglected.
3. Heat transfer through the water surface. This is a major component of the heat balance and the primary topic of this paper.

The calculation of water temperature by a computer model is based upon bookkeeping these fluxes and determining the consequent change in temperature.

As with water quality modeling, one may employ various assumptions concerning the internal distribution of heat or temperature within a water body. The simplest assumption is that the water body is isothermal (fully-mixed). This is often inaccurate for deep lakes or embayments, which are vertically thermally stratified, and for flowing streams, which exhibit longitudinally varying temperature. One-dimensional models are typically used for these situations. An example is the one-dimensional temperature model in the QUAL-II stream water quality program (Roesner, Giguere and Evenson, 1977a and 1977b).

This paper focuses on one important aspect of water temperature modeling—the computation of surface heat transfer. Emphasis is placed upon this particular topic because it is fairly complicated and thus prone to errors in application. Further, the surface heat flux calculation has extensive and complex data requirements. The means to fill these requirements are not well documented in the literature, although there are many helpful "tricks of the trade" that can be used to assemble the needed data. The purpose of this paper is to describe various techniques to develop input data.

Measurement Units

The measurement units in surface heat transfer calculations have long been a problem. In this paper, I will use English system units since those remain the most used. For heat flux, the English system units are Btu/ft²/day. In the metric system, the preferred units are watt/m² (1 watt = 1 joule/sec). Nevertheless, the Langley (abbreviated Ly), equal to 1 cal/cm², persists in usage. The following conversions are useful:

$$\begin{array}{lll} 1 \text{ Btu/ft}^2/\text{day} & = 0.0131 \text{ watt/m}^2 & = 0.271 \text{ Ly/day} \\ 1 \text{ watt/m}^2 & = 7.61 \text{ Btu/ft}^2/\text{day} & = 2.07 \text{ Ly/day} \\ 1 \text{ Ly/day} & = 0.484 \text{ watt/m}^2 & = 3.69 \text{ Btu/ft}^2/\text{day} \end{array}$$

SURFACE HEAT TRANSFER COMPUTATION

The techniques and algorithms to model the transfer of heat through the surface of a water body are well established. Probably the most comprehensive reference on surface heat transfer is a 1972 report by Walter O. Wunderlich of the Tennessee Valley Authority (TVA, 1972). Other excellent references are Ryan and Harleman (1973) and Edinger, Brady and Geyer (1974). The QUAL-II computer program documentation (Roesner, Giguere and Evenson, 1977a and 1977b) is also a good source of information, although it references few original sources.

Surface heat flux consists of five components as illustrated in Figure 1. The water is heated by incoming solar (short-wave) radiation and by incoming atmospheric (long-wave) radiation. Solar radiation is the radiation of the sun, less those portions absorbed by clouds, dust, water vapor and other material in the atmosphere, and less the portion reflected by the water surface. Atmospheric radiation is the radiation emitted by clouds and other material in the atmosphere, less reflection at the water surface. The water body cools by emitting long-wave back radiation and by evaporation and heat conduction. Back radiation emission depends upon the temperature of the water body. Evaporation is basically a diffusion process, driven by the gradient of water vapor pressure from the water surface to the overlying air. Conduction is similar, but driven by the gradient in temperature. Typical magnitudes of the five heat flux components are shown in Table 1.

The sum of the five radiation and heat flux terms is the net heat transfer across the water surface. This is a function of the temperature of the water surface and thus it enters into the equation for water temperature. There are two basic methods to compute the net heat transfer: the complete heat budget and the linearized heat exchange method. Each is discussed in turn in the following.

Heat Budget Method

The complete heat budget requires the separate calculation of the individual heat flux components to arrive at the net surface heat flux. The net heat flux is given as:

$$\phi_n = \phi_{sn} + \phi_{an} - \phi_{br} - \phi_e - \phi_c \quad (2)$$

where

ϕ_n	is the net heat flux into the water surface,
ϕ_{sn}	is the net solar (short-wave) radiation into the water surface,
ϕ_{an}	is the net atmospheric (long-wave) radiation into the water surface,
ϕ_{br}	is the back (long-wave) radiation from the water surface,
ϕ_e	is the evaporative heat flux from the water surface, and
ϕ_c	is the conductive heat flux from the water surface.

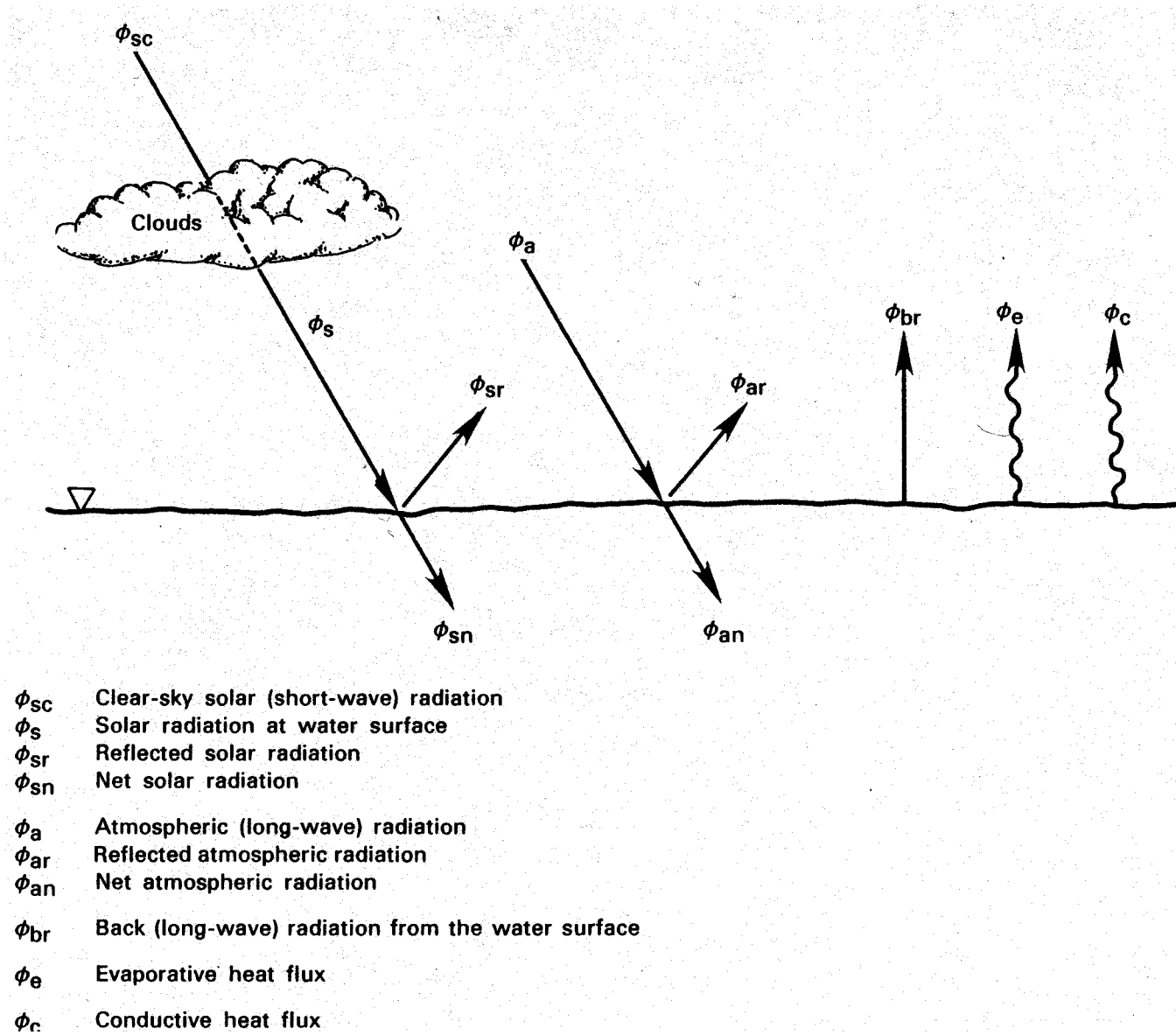


Figure 1. Components of Surface Heat Transfer

TABLE 1

TYPICAL MAGNITUDES OF SURFACE HEAT FLUX COMPONENTS

	<u>Btu/ft²/day</u>	<u>Watt/m²</u>
Solar radiation, ϕ_{sn}	400 to 2500	50 to 350
Atmospheric radiation, ϕ_{an}	1500 to 3000	200 to 400
Back radiation, ϕ_{br}	2000 to 4000	250 to 500
Evaporation, ϕ_e	0 to 2500	0 to 350
Conduction, ϕ_c	-500 to 1500	-70 to 200

All heat flux components have the English system units of Btu/ft²/day. The formulae for the heat flux components are fairly involved and thus tedious for hand calculations. Nevertheless, they are straightforwardly and quickly computed in digital computer programs.

There is a general consensus within the literature on the appropriate formulae to be employed in computing the individual heat budget terms. The following is a brief presentation of the commonly used formulae drawn largely from Ryan and Harleman (1973).

Solar Radiation

The net solar radiation into the water surface is the incoming radiation from the sun, less that absorbed or scattered in the atmosphere, blocked by clouds and reflected at the water surface. The best solar radiation information is from measurements at the site, however these are usually unavailable. Lacking measurements, calculations can be made of the solar radiation and its various attenuation mechanisms, thus computing the radiation at the water surface. The report by Wunderlich (TVA, 1972) gives a detailed explanation of the calculation procedures. Unfortunately these procedures are very complex, even for use in computer programs.

A less complicated alternative is recommended by Ryan and Harleman (1973). They suggest that the clear sky solar radiation be determined from empirical information. The clear sky solar radiation is that reaching the water surface during cloudless conditions. It includes the attenuating effects of atmospheric scattering and absorption, but does not include the effects of cloud cover. The net solar radiation is then computed by accounting for reflectance and cloud cover:

$$\phi_{sn} = 0.94 \phi_{sc} (1 - 0.65 C^2) \quad (3)$$

where ϕ_{sc} is the clear sky solar radiation (Btu/ft²/day), and
 C is the fraction of the sky covered by clouds.

The factor 0.94 accounts for average reflectance at the water surface following the recommendation of Ryan and Harleman (1973). Determination of ϕ_{sc} is discussed subsequently in this paper.

Equation 3 is an approximation in that it assumes average reflectance and employs clear sky solar radiation. The latter is usually an estimate based on average atmospheric attenuation. Equation 3 works well in nearly all circumstances. However, in certain circumstances attenuating mechanisms are much greater than normal. For example, Locher (1981) reported studies in the Pacific Northwest showing significant atmospheric attenuation due to haze during apparently cloudless conditions. For situations such as these, the more complicated formulae described by Wunderlich (TVA, 1972) are required.

Atmospheric Radiation

Water vapor, carbon dioxide, ozone and other atmospheric constituents cause the atmosphere to radiate as an imperfect black body, or gray body. A perfect black body absorbs all incoming radiation and reemits a radiative flux proportional to the fourth power of its absolute temperature. The constant of proportionality is the Stefan-Boltzmann constant. Gray bodies radiate a fraction of the black body radiation, with the fraction being the emissivity. The emissivity of the atmosphere varies with the air temperature, moisture content and other atmospheric variables. Several formulae for atmospheric radiation were recently evaluated against field data by Hatfield et al. (1983). Although past researchers have tended to recommend the formula by Swinbank (1963), Hatfield's study found the Swinbank relation to perform poorly. Based on Hatfield's findings, the formula by Brunt (1932) is adequate:

$$\phi_{an} = 2.05 \times 10^{-8} (1 + 0.149 \sqrt{e_a})(T_a + 460)^4 (1 + 0.17 C^2) \quad (4)$$

where e_a is the vapor pressure 2 meters above the water surface (mm Hg), and
 T_a is the air temperature 2 meters above the water surface ($^{\circ}$ F).

Back Radiation

The water surface, with a nearly constant emissivity of 0.97, approximates a black body. The back radiation from the water surface is given as

$$\phi_{br} = 4 \times 10^{-8} (T_s + 460)^4 \quad (5)$$

where T_s is the water surface temperature ($^{\circ}$ F).

Evaporation

Of the various components of the heat budget, evaporation is the most uncertain. Evaporative heat flux is directly proportional to the rate of evaporative water loss:

$$\phi_e = \mathbf{r} L_v E \quad (6)$$

where E is the evaporation rate (ft/day),
 L_v is the latent heat of evaporation (Btu/lb), and
 \mathbf{r} is the density of water (lb/ft³).

The latent heat of evaporation in Btu/lb is given as a function of temperature as

$$L_V = 1087 - 0.54 T_S \quad (7)$$

Some researchers take L_V as a constant corresponding to $T_S = 212^\circ\text{F}$, the boiling point of water. This is incorrect since T_S will be much less in environmental situations.

There is an extensive literature addressing the calculation of evaporation for both natural and artificially heated water bodies. The general form of the equation for evaporation, E , is:

$$E = F(W)(e_S - e_a) \quad (8)$$

where E is the evaporation rate (ft/day),
 e_S is the saturation vapor pressure of the air at the temperature of the water surface (mm Hg),
 e_a is the vapor pressure at 2 meters above the water surface (mm Hg),
 $F(W)$ is the wind speed function (ft/day/mm Hg), and
 W is the wind speed 2 meters above the water surface (miles/hr).

Usually, Equations 6 and 8 are combined and a constant value of L_V assumed to define ϕ_e as

$$\phi_e = f(W)(e_S - e_a) \quad (9)$$

where $f(W)$ is the heat flux wind speed function (Btu/ft²/day/mm Hg):

$$f(W) = \frac{r L_V}{L_V} F(W)$$

A value of L_V corresponding to a surface temperature of approximately 50 to 70 °F is typically assumed. I will follow that procedure in this paper and assume $L_V = 1060$ Btu/lb as do Ryan and Harleman (1973) and Helfrich et al. (1982). In this way, the values of coefficients in $f(W)$ shown in this paper will be consistent with the literature. Nevertheless, there is little computational effort in computing L_V as a function of T_S . Thus, I recommend a correction factor for computing ϕ_e :

$$\phi_e = \frac{1087 - 0.54 T_S}{1060} f(W) (e_S - e_a) \quad (10)$$

or

$$\phi_e = (1.03 - 5.1 \times 10^{-4} T_S) f(W) (e_S - e_a) \quad (11)$$

Many different expressions have been advanced for the wind speed function $f(W)$. Helfrich et al. (1982) give a systematic review and evaluation of the major formulae. Most expressions adhere to the general form

$$f(W) = a + b W \quad (12)$$

where a is a factor with units $\text{Btu}/\text{ft}^2/\text{day}/\text{mm Hg}$, and
 b is a factor with units $\hat{\text{A}}\text{Btu}\text{-hr}/\text{ft}^2/\text{day}/\text{mm Hg}/\text{mile}$.

Table 2 shows some of the many formulae available and Figure 2 gives an indication of their variability.

Clearly, temperature model users are faced with a bewildering variety of choices in computing evaporation and the evaporative heat flux. The choice is narrowed by defining whether a natural condition is to be modeled or if the water body is artificially heated by thermal discharges. For natural conditions, the Lake Hefner equation is recommended owing to its thorough calibration and long standing:

$$f(W) = 17 W_2 \quad (13)$$

where W_2 is the wind speed at 2 meters above the water surface (miles/hr).

For artificially heated conditions, the study by Helfrich et al. offers guidance. Helfrich et al. recalibrate various evaporation equations to achieve a best match with field data collected at several cooling ponds. The calibration parameter is a single multiplicative factor that is applied to each formula. The equations giving acceptable results after recalibration are the Meyer, Rimsha and Donchenko, Ryan and Harleman, and Throne equations. Overall, Helfrich et al. recommend the Ryan and Harleman equation owing to its sounder theoretical basis. The recalibrated Ryan and Harleman equation is:

$$f(W) = 17.7 \Delta\theta_v^{1/3} + 11.1 W_2 \quad (14)$$

where $\Delta\theta_v$ is the difference between the virtual temperature at the water surface and in the air 2 meters above the water surface ($^{\circ}\text{F}$).

The virtual temperature is used in Equation 14 to account for the buoyancy of the moist air above the heated water surface. The virtual temperature is the temperature of dry air with the same density as the moist. It is defined by Ryan and Harleman (1973) as:

$$\theta_v = \frac{T + 460}{1 + .378 e / p} - 460 \quad (15)$$

TABLE 2
EVAPORATION EQUATIONS

<u>Reference</u>	<u>Equation for f(W)</u>	<u>Conditions</u>
Lake Hefner equation Harbeck (1952)	$17 W_2$	Natural Lakes
Meyer (1942)	$80 + 10 W_2$	Natural Lakes and Ponds
USGS/Chattahoochee River Barnwell (1982)	$60 + 10.2 W_2$	Natural River
QUAL-II Roesner et al. (1977)	$42.5 + 16.9 W_2$	Rivers
Brady, Graves and Geyer (1969)	$70 + W_2^2$	Cooling Ponds
Ryan and Harleman (1973)	$22.4 (\Delta\theta_v)^{1/3} + 14 W_2$	Cooling Ponds
Rimsha and Donchenko (1957)	$61 + 1.47 (T_s - T_a) + 13.3 W_2$	Heated Streams in Winter
Throne (1951)	$67 + 71 W_2$	Cooling Pond

Note: these equations do not include recalibration factors computed by Helfrich et al. (1982).

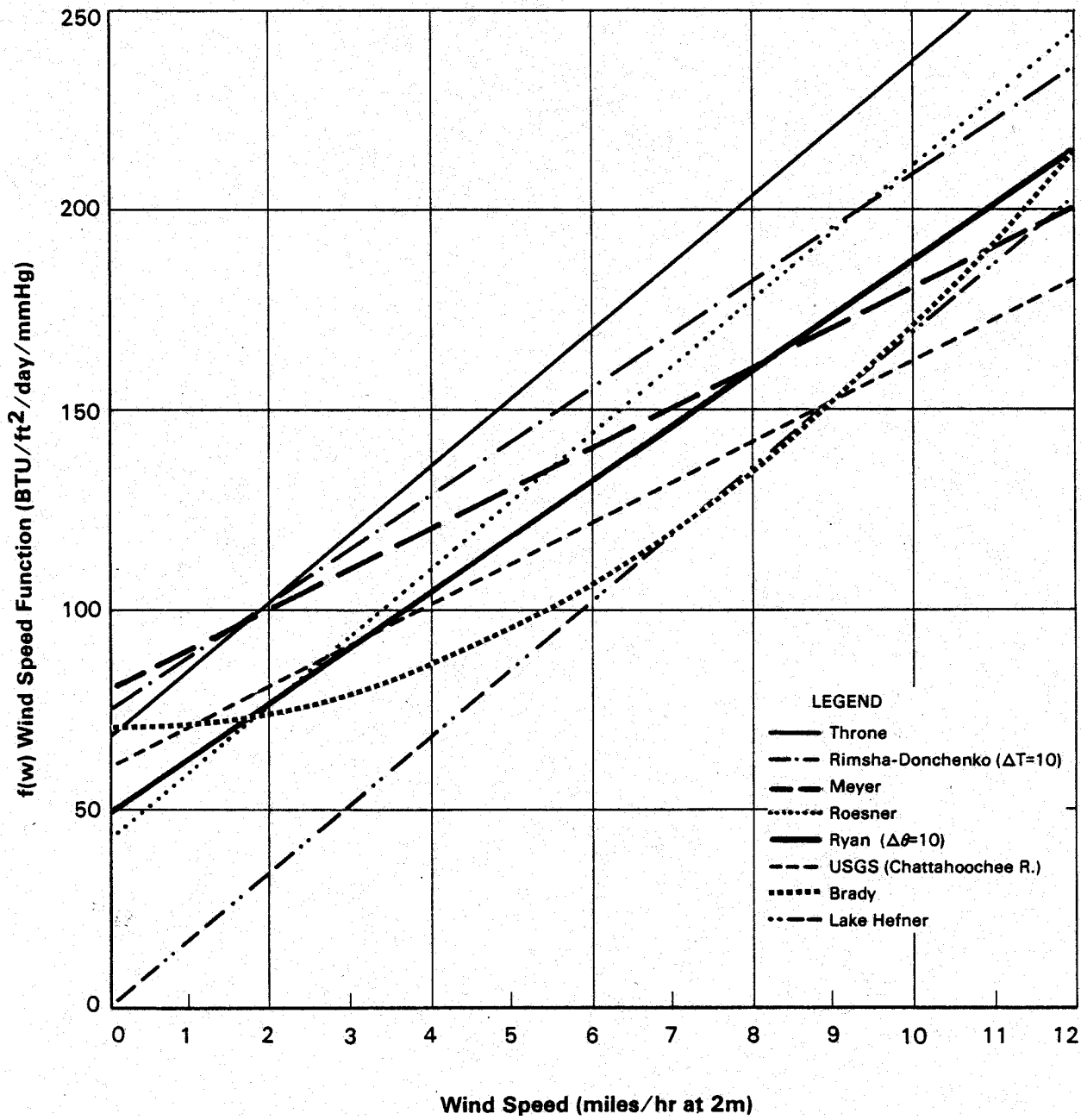


Figure 2. Various Evaporation Wind Speed Functions vs Wind Speed

where θ_v is the virtual temperature ($^{\circ}\text{F}$),
 T is the air temperature ($^{\circ}\text{F}$),
 e is the air vapor pressure (mm Hg), and
 p is atmospheric pressure (mm Hg).

Many computer programs will not accommodate Equation 14 without modification of the program code. For these, the Meyer equation as recalibrated by Helfrich et al. is recommended for artificially heated waters:

$$f(W) = 68 + 8.5 W_2 \quad (16)$$

Alternatively, the wind speed function could be determined by calibration to site data in those applications where sufficient data exist. The formulae of Table 2 should guide such a calibration effort.

In summary, the evaporative heat flux is given as:

$$\phi_e = (1.03 - 5.1 \times 10^{-4} T_s) f(W) (e_s - e_a) \quad (17)$$

where $f(W)$ is selected according to whether the water body is natural or artificially heated.

Conduction

Conduction occurs by a heat diffusion process similar to the moisture diffusion that drives evaporation. Thus, the equation for conductive heat flux is similar in form to that for evaporative heat flux:

$$\phi_c = 0.255 f(W) (T_s - T_a) \quad (18)$$

Net Heat Flux

As stated previously, the net heat flux is the sum of the five component fluxes outlined above. English and metric system equations for the components are summarized in Table 3. The net heat flux is a function of the surface water temperature, the overlying air temperature, moisture content and wind speed, the incoming solar radiation, and the cloud cover and condition of the atmosphere.

Linearized Heat Exchange Method

The linearized heat exchange concept was popularized by John Edinger and others from The Johns Hopkins University. In this approach, the net heat flux is assumed to be a linear function of the surface water temperature:

$$\phi_n = K (T_s - T_E) \quad (19)$$

where K is the surface heat exchange coefficient
 (Btu/ft²/day/ $^{\circ}\text{F}$), and
 T_E is the equilibrium temperature ($^{\circ}\text{F}$).

TABLE 3

SUMMARY OF EQUATIONS FOR SURFACE HEAT FLUX COMPONENTS

<u>Component</u>	<u>English System</u>	<u>Metric System (S.I.)</u>
<u>Heat Flux Components:</u>		
	ϕ in $\hat{\text{A}}\text{tu}/\text{ft}^2/\text{day}$	ϕ in watt m^2
Net Solar Radiation	$\phi_{\text{sn}} = 0.94 \phi_{\text{sc}} (1 - 0.65 c^2)$	$\phi_{\text{sn}} = 0.94 \phi_{\text{sc}} (1 - 0.65 c^2)$
Net Atmospheric Radiation	$\phi_{\text{an}} = 2.05 \times 10^{-8} (1 + 0.149 \sqrt{e_a}) (\hat{\delta}_a + 460)^4 (1 + 0.17 c^2)$	$\phi_{\text{an}} = 2.89 \times 10^{-8} (1 + 1.29 \sqrt{e_a}) (T_a + 273)^4 (1 + 0.17 c^2)$
Back Radiation	$\phi_{\text{br}} = 4.0 \times 10^{-8} (T_s + 460)^4$	$\phi_{\text{br}} = 5.44 \times 10^{-8} (T_s + 273)^4$
Evaporation	$\phi_e = (1.03 - 5.1 \times 10^{-4} T_s) f(W) (e_s - e_a)$	$\phi_e = (1.01 - 9.1 \times 10^{-4} T_s) f(W) (e_s - e_a)$
Conduction	$\phi_c = 0.255 f(W) (T_s - T_a)$	$\phi_c = 0.60 f(W) (T_s - T_a)$
<u>Wind Speed Functions:</u>		
	$f(W)$ in $\text{Btu}/\text{ft}^2/\text{day}/\text{mm Hg}$	$f(W)$ in $\text{watt}/\text{m}^2/\text{mb}$
Natural Conditions	$f(W) = 17 W_2$	$f(W) = 3.84 W_2$
Artificially heated conditions (Ryan and Harleman* 1973)	$f(W) = 17.7 \Delta\theta_v^{1/3} + 11.1 W_2$	$f(W) = 2.18 \Delta\theta^{1/3} + 2.51 W_2$
Artificially heated conditions (Meyer* 1942)	$f(W) = 68 + 8.5 W_2$	$f(W) = 6.87 + 1.92 W_2$
<u>Parameters:</u>		
C, cloud cover	fraction of sky	fraction of sky
e_a , air vapor pressure at 2 m above water	mm mercury (mm Hg)	millibar (mb)
E_s , saturation vapor pressure at temperature T_s	mm mercury	Millibar
T_a , air temperature	degrees F	degrees C
T_s , water surface temperature	degrees F	degrees C
W_2 , wind speed at 2 m above water	miles/hour	m/s
$\Delta\theta_v$, virtual temperature difference between water surface and 2 m (see text)	degrees F	degrees C

* Wind speed functions recalibrated by Helfrich et al. (1982)

Equation 19 entails two parameters that are artificial, but nevertheless useful and intuitive. The equilibrium temperature is the water surface temperature that is in equilibrium with the environment: the net surface heat transfer is zero. Water bodies continually seek their equilibrium temperature, losing or gaining heat as required. But since environmental conditions change continuously, the equilibrium temperature also changes and a water body is seldom at its equilibrium temperature.

The surface heat exchange coefficient is the incremental change in the rate of net heat transfer per unit change in surface water temperature. It varies with the surface temperature and thus should be recalculated as the water temperature changes.

The linearized heat exchange method is attractive since it permits analytical solutions for a variety of water temperature problems. However, it is less accurate than the heat budget method and not suitable for detailed design or analysis studies. A general recommendation is that the linearized method not be used in computer modeling since there is no difficulty or additional data required to use the more accurate heat budget method.

Despite the recommendation that the linearized method not be used, the equilibrium temperature concept is very useful and attractive. It is particularly helpful in screening data—for example in reviewing historical records to select a critical period for design. Extended periods of extremely high equilibrium temperature are those in which thermal aquatic impacts will be greatest. These same periods are when cooling ponds and similar heat rejection systems perform their worst. Thus, the equilibrium temperature is a useful variable in selecting simulation periods from long data records. It is also valuable to understanding water temperature trends in transient computer simulations. Table 4 is a BASIC-language computer program for calculation of the equilibrium temperature.

METEOROLOGICAL DATA REQUIREMENTS

Probably the greatest burden in water temperature modeling is the extensive input data requirement. The calculation of the heat budget requires meteorological data characterizing the air temperature, humidity, wind speed, cloudiness, and solar radiation at the study site. It is rare that a complete set of data is available from measurements at a site, and thus other sources must be sought.

The most comprehensive source of meteorological data is the published observations of the National Climatic Center in Asheville, NC. The center publishes data for many locations throughout the country in a number of formats. Monthly summaries are published for each state in the publication Climatological Data and daily and 3-hourly data are published each month for selected weather stations in Local Climatological Data. Data are also available on magnetic tape for computer modeling of long periods.

TABLE 4
 BASIC-LANGUAGE COMPUTER PROGRAM FOR CALCULATION
 OF EQUILIBRIUM TEMPERATURE
 (revised for Microsoft QuickBASIC)

```

DECLARE FUNCTION SATVP! (T!)
DECLARE SUB CLEARSKY (S!)
REM =====
REM EQUILIBRIUM TEMPERATURE CALCULATION
REM =====
REM REF: P. SHANAHAN, "WATER TEMPERATURE MODELING: A
REM PRACTICAL GUIDE", PROCEEDINGS OF STORMWATER AND
REM WATER QUALITY MODEL USERS GROUP MEETING,
REM APRIL 12-13, 1984, REPORT EPA-600/9-85-003.
REM
REM DIM U(3), H(3)
REM
REM FORMATTED OUTPUT FILE
REM
REM OPEN "THERMAL.OUT" FOR OUTPUT AS #1
REM
REM A = 0
REM B = 0
REM
10 PRINT " INPUT T, W, R, S, C, F"
PRINT " T IS THE AIR TEMPERATURE, DEG. F"
PRINT " W IS THE WIND SPEED, MPH AT 2 M"
PRINT " R IS THE RELATIVE HUMIDITY, PERCENT"
PRINT " S IS THE OBSERVED SOLAR RADIATION, BTU/SQ FT/DAY"
PRINT " (IF S IS ZERO, A VALUE WILL BE COMPUTED)"
PRINT " C IS THE CLOUD COVER, FRACTION"
PRINT " F IS THE WIND SPEED FUNCTION:"
PRINT " F=1 FOR LAKE HEFNER"
PRINT " F=2 FOR MODIFIED RYAN"
PRINT " F=3 FOR MODIFIED MEYER"
PRINT " F=4 FOR USER SPECIFIED"
50 PRINT " "
PRINT " INPUT T, W, R, S, C, F"
PRINT " ENTER ZEROS TO STOP"
REM
REM GET USER INPUT DATA
REM
INPUT T, W, R, S, C, F
IF (T = 0 AND W = 0 AND R = 0 AND S = 0 AND C = 0 AND F = 0) THEN
  STOP
  CLOSE #1
  END IF
IF (W < 0 OR R <= 0 OR R > 100 OR S < 0 OR C < 0 OR C > 1 OR
  (F <> 1 AND F <> 2 AND F <> 3 AND F <> 4)) THEN
  PRINT " "
  PRINT " INPUT ERROR - PLEASE RE-ENTER DATA"
  PRINT " "
  GOTO 10
END IF
IF (F = 4) THEN
  PRINT " INPUT A,B FOR WIND FUNCTION F(W) = A+B*W"
  INPUT A, B
  END IF
REM
REM COMPUTE METEOROLOGICAL CONSTANTS
REM
REM CONVERT UNITS
R = R / 100
T4 = T + 460
REM
REM COMPUTE SOLAR RADIATION
IF (S = 0) THEN
  CALL CLEARSKY(S2)
  S = S2 * (1 - .65 * C ^ 2)
  END IF
H3 = .94 * S
REM
REM COMPUTE AIR VAPOR PRESSURE AND VIRTUAL TEMPERATURE
E1 = SATVP(T) * R
T3 = T4 / (1 - .378 * E1 / 760) - 460
REM
REM COMPUTE LONG WAVE (ATMOSPHERIC) RADIATION
H2 = 2.1E-08 * (1 + .149 * SQR(E1)) * T4 ^ 4 * (1 + .17 * C ^ 2)
REM
REM USE BISECTION METHOD TO COMPUTE EQUILIBRIUM TEMPERATURE
REM
I1 = 1
I2 = 3
U(1) = T - 5
U(2) = T
U(3) = T + 5
Z1 = 0
100 FOR I = I1 TO I2
  Z1 = Z1 + 1
  IF (Z1 > 100) THEN
    PRINT " "
    PRINT " FAILURE TO CONVERGE -- RUN ENDING"
    CLOSE #1
    STOP
    END IF
  U1 = U(I) + 460
  REM
  REM COMPUTE LONGWAVE BACK RADIATION
  H1 = 4E-08 * U1 ^ 4
  E2 = SATVP(U(I))

```

TABLE 4 (continued)
 BASIC-LANGUAGE COMPUTER PROGRAM FOR CALCULATION
 OF EQUILIBRIUM TEMPERATURE

```

    IF (F = 1) THEN
      LAKE HEFNER EQUATION
      F1 = 17 * W
    ELSEIF (F = 2) THEN
      MODIFIED RYAN EQUATION
      D2 = U1 / (1 - .378 * E2 / 760) - 460
      D2 = D2 - T3
      D3 = .0024 * W ^ 3
      IF (D2 < D3) THEN D2 = D3
      F1 = 17.7 * D2 ^ .3334 + 11.1 * W
    ELSEIF (F = 3) THEN
      MODIFIED MEYER EQUATION
      F1 = 68 + 8.5 * W
    ELSE
      USER SPECIFIED WIND FUNCTION
      F1 = A + B * W
    END IF

    COMPUTE EVAPORATIVE HEAT FLUX
    H4 = F1 * (E2 - E1)
    IF (H4 < 0) THEN H4 = 0
  COMPUTE HEAT CONDUCTION
  H5 = F1 * .255 * (U(I) - T)
  COMPUTE TOTAL HEAT FLUX
  H(I) = H2 + H3 - H1 - H4 - H5
  DETERMINE IF H HAS CONVERGED TO 1 BTU/SQ FT/DAY OR LESS
  IF (ABS(H(I)) < 1) THEN 200
  NEXT I

  REM   PREPARE FOR NEXT ITERATION
  I1 = 2
  I2 = 2
  IF (H(1) < 0) THEN
    U(1) = U(1) - 10
    H(1) = 0
    I1 = 1
  ELSEIF (H(3) > 0) THEN
    U(3) = U(3) + 10
    H(3) = 0
    I2 = 3
  ELSE
    J1 = 1
    IF ((H(1) * H(2)) < 0) THEN J1 = 3
    U(J1) = U(2)
    H(J1) = H(2)
  END IF
  U(2) = .5 * (U(1) + U(3))
  GOTO 100

  REM   EQUILIBRIUM TEMPERATURE FOUND
  
```

```

  REM   PRINT " "
  200  PRINT USING "   EQUILIBRIUM TEMPERATURE = ###.# DEG F"; U(2)
  PRINT " "
  PRINT " "
  PRINT #1, USING "###.#"; U(2)
  GOTO 50
  END

  REM   =====
  REM   SATURATION VAPOR PRESSURE FUNCTION
  REM   =====
  REM   FUNCTION SATVP (TS)
  REM   SATVP = 25.4 * EXP(17.62 - 9500.8 / (TS + 460))
  REM   END FUNCTION
  
```

Some other, less comprehensive sources of data are useful for rough calculations. These are the "Climatic Atlas of the United States", published by the National Oceanic and Atmospheric Administration (1977) and an EPA report, "Effect of Geographical Variation on the Performance of Recirculating Cooling Ponds" (Thackston, 1974). The EPA publication also includes extreme monthly conditions which are useful to evaluate surface heat transfer when it is at its least.

The representativeness of off-site data is rarely addressed. Nevertheless, it is an important matter. The weather bureau station nearest the site need not be the most representative. It may fall in a different geographic or climatic province, and thus be inappropriate. A rigorous attempt to synthesize on-site data was made by Jirka et al. (1977) for the site of the North Anna Power Station in Virginia. They used statistical techniques to correlate a single year of on-site meteorological data with coincident records at three surrounding weather stations. Then, they employed their computed statistical correlations to generate a long-term synthetic record for the site from the records of the weather stations. A similar procedure is recommended for detailed design studies where the representativeness of off-site data is uncertain. In any study, the modeler should consider the local climatology to determine the most representative station for off-site meteorological data.

Having obtained data, it is often necessary to convert it to a format compatible with the heat budget formulae. Air temperature presents no problem, but humidity, wind speed, cloudiness and solar radiation often need adjustments or conversions.

Humidity Data

The humidity of air may be expressed directly as relative humidity, and indirectly through the dew point or wet bulb temperature. The wet bulb or dew point, together with the air (or dry bulb) temperature, may be used to compute relative humidity using a psychometric chart. The chart, with instructions, is given in the Handbook of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1981) and numerous other publications. Another possible conversion method from wet bulb to relative humidity is available by inverting an empirical equation given by Thackston (1974)

$$T_{wb} = (0.655 + 0.36 R_H) T_a \quad (20a)$$

or

$$R_H = 2.78 \frac{T_{wb}}{T_a} - 1.82 \quad (20b)$$

where T_{wb} is the wet bulb temperature ($^{\circ}F$), and
 R_H is the relative humidity (expressed as a fraction).

This equation is valid for relative humidity less than about 95%. TVA (1972) gives the following conversion from dew point temperature to air vapor pressure over water:

$$e_a = \exp\left[2.3026\left(\frac{7.5 T_d - 236.9}{T_d + 395.5} + 0.6609\right)\right] \quad (21)$$

where T_d is the dew point temperature of the air ($^{\circ}F$).

The humidity conditions of the air must be expressed as the water vapor pressure in the equations for calculation of evaporative and conductive heat flux. The vapor pressure of the air is computed as:

$$e_a = R_H e_{sat}$$

where e_{sat} is the saturation vapor pressure (mm Hg).

Calculation of surface heat transfer requires that the saturation vapor pressure be determined as a function of temperature. Extremely accurate and precise tables of this function are found in the Smithsonian Meteorological Tables (List, 1971). Several different empirical formulae have been proposed to compute the saturation vapor pressure as a function of temperature. For environmental temperatures, the empirical equation by Thackston (1974) is virtually indistinguishable from the tabulated function:

$$e_{sat} = 25.4 \exp\left(17.62 - \frac{9500.8}{T + 460}\right) \quad (22)$$

where T is the temperature ($^{\circ}F$).

In computing evaporative heat flux, the vapor pressure at the water surface is computed by assuming it is saturated ($R_H = 1.0$) and at the temperature of the water. The vapor pressure at a height above the surface is based upon ambient temperature and relative humidity of the air.

Wind Speed

The height above the water or ground surface at which the wind is measured is an important consideration in the use of wind speed data. Often, the measuring height is unknown. But if it is available, the speed may be adjusted to the height presumed by the heat transfer formulae (usually 2 meters). Based upon an assumed logarithmic wind speed profile, Ryan and Harleman (1973) give the following adjustment relation:

$$\frac{W_z}{W_{z_1}} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)} \quad (23)$$

where W_z is the (desired) wind speed at height z ,
 W_{z_1} is the (known) wind speed at height z_1
 z is the height above the water surface presumed by the surface heat transfer formula (m),
 z_1 is the height above the water at which the wind speed is known (m), and
 z_0 is the wind roughness height (m).

Helfrich et al. (1982) discuss the selection of z_0 . A value of $z_0 = 0.001$ meter is a good approximation for most wind conditions. At high wind speeds, waves form on the water surface and increase z_0 .

Cloudiness

The cloud cover of the sky is usually recorded as the percent (or number of tenths) of the sky that is covered by clouds. Occasionally, the quantity percent possible sunshine will be given. The conversion from percent possible sunshine to cloud cover can be made using an equation derived from relations given by TVA (1972):

$$C = [1.2(1 - P^{2/3})]^{1/2} \quad (24)$$

where C is the cloud cover (expressed as a fraction) and
 P is the possible sunshine (expressed as a fraction).

Solar Radiation

Direct measurements of solar radiation are rare, and consequently these data must be determined by other means. Neglecting the influence of the clouds, the clear sky solar radiation may be determined as a function of the geographical latitude, the time of year, and the hour of the day. TVA (1972), Brock (1981) and any of a variety of references from the meteorological and heating and air conditioning engineering literature give formulae to calculate the clear sky solar radiation. Unfortunately, these formulae are complex and cumbersome, even for computer calculations. The complexity derives from the need for esoteric parameter values and the fact that clock time cannot be used in the calculations, only solar time (i.e., relative to true solar noon) can be used.

If the modeler desires only daily average values of solar radiation, there are simple alternatives. For example, Thackston (1974) employs curve-fit equations that are reasonably accurate and amenable to both hand and computer calculations. Table 5 is a BASIC-language computer program utilizing his

TABLE 5
 BASIC-LANGUAGE COMPUTER PROGRAM FOR CALCULATION
 OF DAILY AVERAGE CLEAR SKY SOLAR RADIATION
 (revised as subroutine for Microsoft QuickBASIC)

```

REM      =====
REM      CALCULATION OF CLEAR SKY SOLAR
REM      RADIATION AT WATER SURFACE
REM      IN UNITS OF BTU/SQ FT/DAY
REM      =====
REM      REF: THACKSTON, 1974,
REM           REPORT EPA-660/2-74-85
REM
REM      SUB CLEARSKY (S)
REM
REM      DIM DAY(12), C1(21), C2(21), C3(21)
REM
REM      SET UP CONSTANTS FOR CLEAR-SKY RADIATION CALCULATION
REM      DAY OF YEAR ARRAY
REM      FOR I = 1 TO 12
REM      READ DAY(I)
REM      NEXT I
REM      DATA 0,31,59,90,120,151,181,212,243,273,304,334
REM
REM      COEFFICIENTS FOR CURVE FIT EQUATIONS
REM      FOR I = 1 TO 21
REM      READ C1(I), C2(I), C3(I)
REM      NEXT I
REM      DATA 80.155, 29.207, 1.679
REM      DATA 79.371, 30.236, 1.713
REM      DATA 78.566, 31.219, 1.710
REM      DATA 77.604, 32.145, 1.740
REM      DATA 76.655, 33.156, 1.728
REM      DATA 76.041, 34.133, 1.694
REM      DATA 75.060, 35.194, 1.737
REM      DATA 74.046, 35.938, 1.734
REM      DATA 73.161, 36.834, 1.727
REM      DATA 72.248, 37.699, 1.738
REM      DATA 71.390, 38.598, 1.721
REM      DATA 70.394, 39.413, 1.730
REM      DATA 69.350, 40.188, 1.741
REM      DATA 68.362, 40.982, 1.739
REM      DATA 67.281, 41.706, 1.742
REM      DATA 66.240, 42.442, 1.736
REM      DATA 65.197, 43.128, 1.740
REM      DATA 64.113, 43.788, 1.739
REM      DATA 63.010, 44.471, 1.739
REM      DATA 61.911, 45.020, 1.740
REM      DATA 60.782, 45.639, 1.735
REM
REM      INPUT LATITUDE AND DATE
REM      PRINT " "
REM      1010 PRINT " ENTER SITE LATITUDE"
REM      PRINT " (26 TO 46 DEGREES)"
REM      INPUT L
REM      L1 = INT(L)
REM      L3 = L1 - 25
REM      L2 = INT(L + .99)
REM      L4 = L2 - 25
REM      IF (L1 < 26 OR L1 > 46) THEN
REM      PRINT "INVALID VALUE - PLEASE RE-ENTER"
REM      GOTO 1010
REM      END IF
REM      IF (L2 < 26 OR L2 > 46) THEN
REM      PRINT "INVALID VALUE - PLEASE RE-ENTER"
REM      GOTO 1010
REM      END IF
REM      PRINT " "
REM      PRINT " ENTER DATE AS MONTH,DAY"
REM      INPUT D7, D8
REM      D = DAY(D7) + D8
REM
REM      COMPUTE CLEAR SKY SOLAR RADIATION
REM
REM      D6 = 2 * 3.14159 * D / 366
REM      S = C1(L3) - C2(L3) * SIN(C3(L3) + D6)
REM      IF (L1 <> L2) THEN
REM      S2 = C1(L4) - C2(L4) * SIN(C3(L4) + D6)
REM      L1 = L - L1
REM      L2 = L2 - L
REM      S = L2 * S + L1 * S2
REM      END IF
REM      S = 24 * S
REM      CORRECT FOR ABSORBTION
REM      S = S / .94
REM
REM      DISPLAY RESULT
REM
REM      PRINT " "
REM      PRINT USING " AT LATITUDE ##.# ON ##/##"; L; D7; D8
REM      PRINT USING " COMPUTED CLEAR SKY SOLAR RADIATION IS ##### BTU/SQ FT/DAY"; S
REM      PRINT " "
REM      EXIT SUB
REM      END SUB

```

equations. Another very workable alternative for hand calculation is a graphical look-up, as presented by Hamon, Weiss and Wilson (1954). Figure 3 is a graph of clear sky solar radiation based on their empirical results.

As stated above, distribution of solar radiation throughout the day can be difficult. If one only desires to construct a representative daily variation in solar radiation, then the formulae of TVA (1972) or Brock (1981) are quite useful. However, if one wishes to construct a diurnal variation to be used with measured data, then the differences between clock time and solar time require careful attention. For example, I have attempted in the past to back-calculate cloud cover from the differences between measured solar radiation at a site (ϕ_s in Figure 1) and a computed value of clear sky solar radiation (ϕ_{CS}). The procedure worked fairly well for daily averages (Wells et al., 1982). But it worked very poorly for hourly values due to inexact coordination of clock time and solar time.

For some problems, a hand calculation procedure for diurnal variation of solar radiation is desirable. For these, it is possible to distribute daily solar radiation throughout the day using data given in Chapter 27 of the ASHRAE Handbook, 1981 Fundamentals. In the handbook, tables of solar position and intensity for various latitudes give the direct normal irradiation distribution by hours during the day. The normalization of the hourly values by the sum for the day supplies a set of distribution constants. These distribution constants may be applied to the daily average clear sky solar radiation to construct the diurnal variation of solar radiation.

One final, but very important footnote applies to both the solar radiation and atmospheric radiation components. These radiation fluxes can be measured directly to supply far more accurate data than the calculation procedures above.

SUMMARY

This paper is a review of the surface heat transfer calculations necessary to model water temperature in surface water bodies. The paper recommends the use of the heat budget technique as more accurate than the linearized method. The linearized method is based on the equilibrium temperature and surface heat exchange coefficient. Within the heat budget technique, there are the following heat flux components and recommended procedures:

Solar Radiation - It is best to measure this directly. If measurements are not available, clear sky solar radiation may be estimated from Figure 3 or Table 5 and then modified for cloud cover and reflectance (Equation 3). A more exact procedure is recommended for areas with prevalent haze, dust or high water vapor.

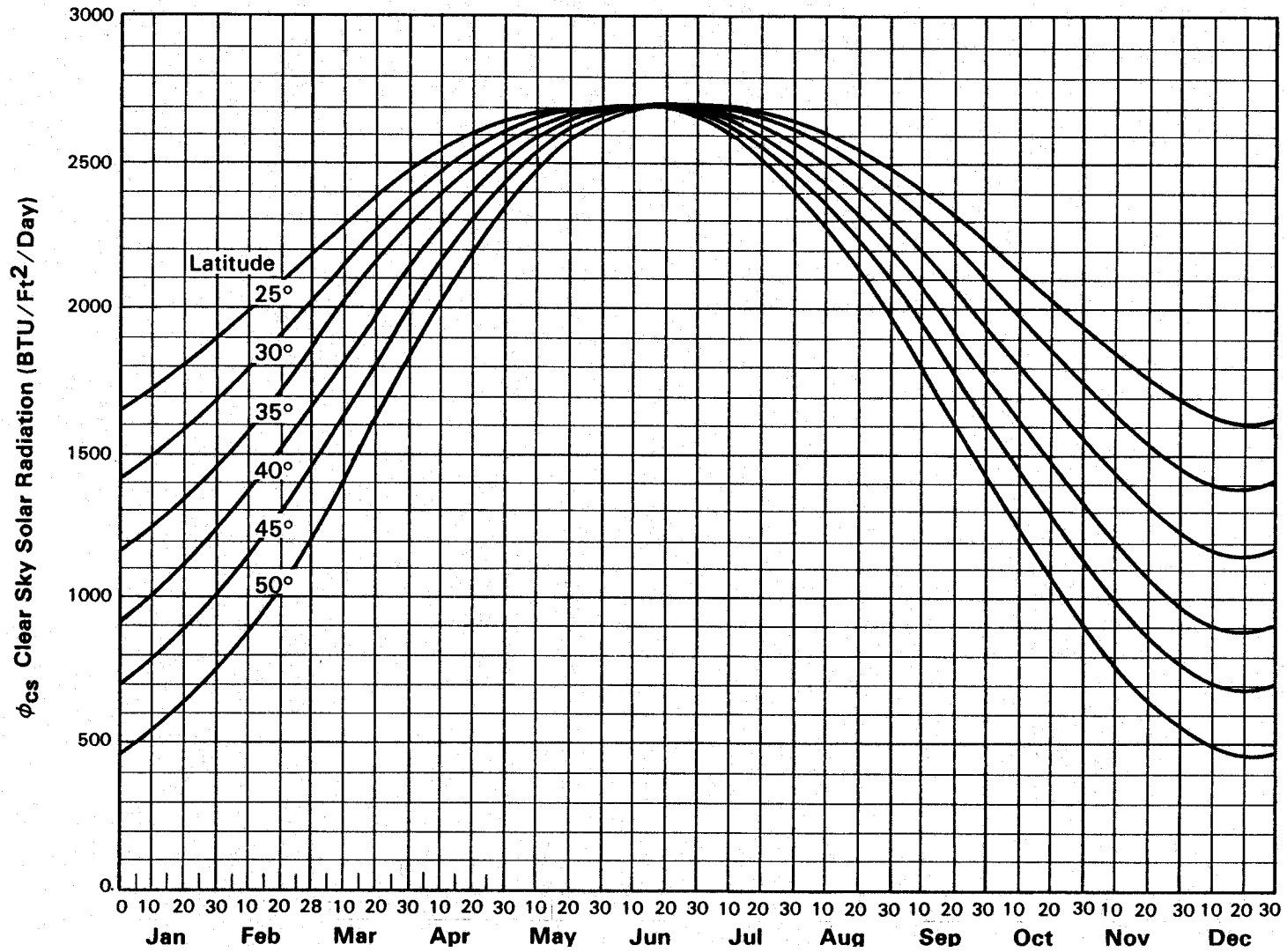


Figure 3. Clear Sky Solar Radiation According to Hamon, Weiss and Wilson (1954)

- Atmospheric Radiation - It is best to measure this directly. If measurements are not available, Brunt's equation (Equation 4) is recommended.
- Back Radiation - This flux is accurately determined by Equation 5.
- Evaporation - Evaporative heat flux is computed as the product of the latent heat of evaporation, the gradient in vapor pressure from the water surface to the overlying air, and an empirical wind speed function. The Lake Hefner wind speed function is recommended for natural water bodies, the Ryan-Harleman for artificially heated. In computer programs that will not accommodate the Ryan-Harleman equation, the Meyer equation is a good substitute. Both the Ryan-Harleman and Meyer equations should include the recalibration factors by Helfrich et al. (1982).
- Conduction - Conductive heat flux is the product of a constant of proportionality the gradient in temperature from the water surface to the overlying air, and the wind speed function.

Table 3 is a complete summary of the recommended equations for the heat budget. Equations in both English and metric units are included in Table 3.

The input data required for water temperature modeling are extensive. Five types of data are required: the air temperature, the wind speed, the relative humidity, the cloud cover, and the solar radiation or an estimate of clear sky solar radiation. This paper includes descriptions of procedures to manipulate data as follows:

- Humidity - conversion from wet bulb to relative humidity
conversion from dew point to relative humidity
calculation of saturation vapor pressure
calculation of vapor pressure
- Wind Speed - adjustment for measurement height
- Cloudiness - conversion from percent possible sunshine to cloud cover
- Solar Radiation - graphical estimation of clear sky solar radiation
computer program to calculate estimated clear sky solar radiation
diurnal distribution of clear sky solar radiation

The paper also includes a computer program to compute the equilibrium temperature as a function of the meteorological variables above.

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