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Evaporation Estimation for Lake Okeechobee in South Florida

by

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EXECUTIVE SUMMARY

Lake Okeechobee is the second largest fresh water lake in the United States located in subtropical South Florida. Seven methods of evaporation estimation methods were evaluated using site measured data. The analysis used five year weather data measured inside the lake. Simple models are recommended to estimate daily lake evaporation from solar radiation or solar radiation and maximum air temperature. An average annual evaporation of 132 cm (52 inches) is reported from five years analysis (1993 to 1997). The water budget method resulted in a 10% higher estimation. Pan coefficient was found to be site specific. Monthly pan coefficient and annual average pan coefficient is produced for seven pan evaporation stations in the vicinity of Lake Okeechobee. Using the recommended models, Lake Okeechobee daily evaporation can be reported at the end of the day and be part of the daily system storage report of the South Florida Water Management District.

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INTRODUCTION

Evaporation is the process by which water is converted to water vapor and transported to the atmosphere. Evaporation from lakes (E_o) depends on the availability of energy and the mechanism of mass and energy transfer, depth and the surface area of the lake. E_o is a function of solar radiation, temperature, wind speed, vapor pressure deficit, atmospheric pressure and the surrounding environment. The annual lake evaporation for the continental United States is estimated to vary between 51 cm (20 inches) in the northeast and 218 cm (86 inches) in Southern California (Viessman et al., 1977). Evaporation, being a major component of the water cycle, is important in water resources development and management.

Evaporation from lakes and reservoirs is estimated indirectly from pan evaporation. Usually, pan data is reduced by a factor to estimate E_o. The factor depends on season, location and the specific pan in use. Water budget of the water body is also used to estimate evaporation losses. Energy based and/or energy and aerodynamic based evapotranspiration estimation models are also applied to estimate evaporation from meteorologic parameters. Other lake evaporation simulation methods include a mass-transfer method where E_o is estimated from wind speed, vapor pressure deficit and a calibration coefficient (Harbeck, 1962; Hostetler and Bartlein, 1990; Shuttleworth, 1993).

Lake Okeechobee is the second largest fresh water lake in the United States (Figure 1). It is located at 27° Latitude and 81° Longitude in subtropical South Florida. It has a surface area of 1,732 km^2 (680 $mile^2$) and mean depth of 2.7 m (8.86 ft) (Jin et al., 1998). Historically, Lake Okeechobee has attained a maximum of 5.72 m (18.76 ft) (November 2, 1947) and a minimum of 2.98 m (9.77 ft) (July 30, 1981) NGVD water surface elevation with a mean of 4.4 m (14.43 ft) NGVD. Inflow to the lake is generally from the north and northwest. Outflow is generally to the east, southeast and south. Historical mean inflow to the lake is 183,650 ha-m (1,488,816 ac-ft); mean outflow is 137,304 ha-m (1,113,099 ac-ft) and mean annual rainfall as observed with 27 gages around the lake is 118.4 cm (46.6 inches) for the period 1963 to 1997.

Shallow lake evaporation estimates have been reported in the literature. Estimates of mean annual evaporation from shallow lakes and reservoirs in the continental United States show that the annual lake evaporation for the Lake Okeechobee area is about 129.5 cm (51 inches) per year (Viessman et al., 1977). Average maximum potential evaporation map by Visher and Hughes (1975) indicates an annual value of 127 cm (50 inches) for Lake Okeechobee. Waylen and Zorn (1998) presented annual evaporation estimation map for Florida and Lake Okeechobee show about 125.7 cm (49.5 inches) per year. Literature citation of Lake Okeechobee annual evaporation estimates based on historical water budgets is reported in volumetric units by Allen et al. (1982). Estimates of 130.6 cm (51.4 inches), 127 cm (50.0 inches), 125.7 cm (49.5 inches), 138.7 cm (54.6 inches), 142.7 cm (56.2 inches) and 146.8 cm (57.8 inches) per year were derived from the various reports using the given surface area of the lake.

The purpose of this study is to develop a reliable and applicable method for daily estimation of evaporation for Lake Okeechobee and incorporate the results in the daily system storage report of the South Florida Water Management District.

LAKE EVAPORATION ESTIMATION METHODS

Pan Method

Various lake or open water evaporation estimation methods and equations have been applied throughout the years. The most common lake evaporation estimation method is the reduction of standard pan evaporation data using the following equation.

$$E_o = K_p E_{pan} \qquad (1)$$

Where E_o is lake evaporation; K_p is coefficient and E_{pan} is pan evaporation. A limitation of this method is that the coefficient is dependent on the local environment of the pan including pan operations or management. Historical literature on the use of pan data to estimate evapotranspiration and its limitations, required cautions are summarized by Jensen et al. (1990). Table 1 summarizes site information of pan evaporation stations in the vicinity of Lake Okeechobee. Currently, the USACE Jacksonville District, estimates daily Lake Okeechobee evaporation from an average of two pans (S308 and S77; Fig. 1) with a K_p value of 0.75. The average annual estimated E_o for Lake Okeechobee based on K_p value of 0.75 and pan station S308 for which long term data was available is 154 cm (60.7 inches) (Table 2). Data is not available for S77. Table 2 shows average monthly and annual pan evaporation for each pan station for the study period of 1993 to 1997. Table 3 illustrates that K_p is site dependent and reference to E_0 estimation from pan should include the site name as the specific environment of the pan including its operation or management is a factor in the readings.

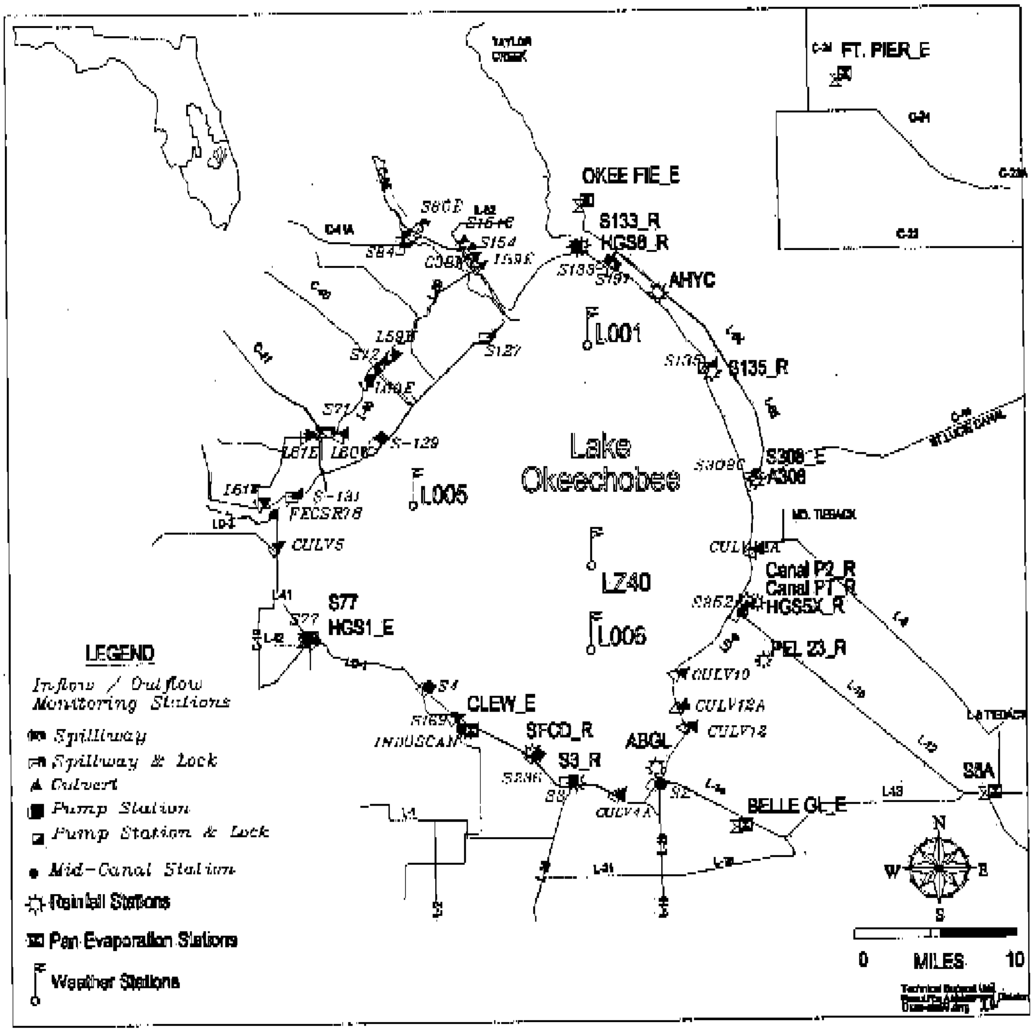

Figure 1. Lake Okeechobee Monitoring Stations.

Table 1. Pan Evaporation Stations in the Vicinity of Lake Okeechobee.

Symbol	Station	DBkey[*]	Period of Record	Number of. years[†]
OK	OKEE FIE_E	06348	10/01/83-06/30/98	15
FT	FT PIER_E	06347	03/01/82-07/31/98	16
HG	HGS1_E	06381[‡]	1926-1948	22
		06364	08/01/48-07/25/98	50
CL	CLEW_E	06382[‡]	1941-1967	26
		07189[‡]	1968-1982	14
		06365	01/01/70-01/31/98	28
		15208	01/01/83-12/31/90	7
BG	BELLE GL_E	07188[‡]	1925-1940	15
		06357	01/01/41-05/01/98	57
		15207	11/01/79-12/31/90	11
		15342	02/01/92-06/30/98	6
S5A	S5A_E	06331	01/01/57-06/30/98	41
		16272	01/01/63-07/25/95	32
		15206	11/01/79-12/31/90	11
S308	S308_E	06376	07/24/96-07/15/98	2
		06376	10/01/48-12/31/54	6
		06380[‡]	1941-1945	4
		07193[‡]	1946-1947	1

[*] Station reference and axis key in SFWMD database DBHYDRO.

[†] Indicates approximate number of years.

[‡] Indicates monthly summation data only.

Table 2. Monthly Average Pan Evaporation (E_{pan}) in cm (inches) Around Lake Okeechobee (1993 to 1997).

Month	Station							
	OK	HG	CL	BG	S5A	FT	S308	Average[†]
Jan	8.41 (3.31)	9.40 (3.70)	8.41 (3.31)	9.17 (3.61)	7.48 (2.94)	9.01 (3.55)	10.64 (4.19)	8.68 (3.42)
Feb	10.19 (4.01)	11.24 (4.43)	10.19 (4.01)	10.78 (4.24)	8.15 (3.21)	9.89 (3.89)	11.56 (4.55)	10.16 (4.00)
Mar	15.45 (6.08)	16.10 (6.34)	15.45 (6.08)	16.43 (6.47)	12.37 (4.87)	14.95 (5.89)	20.65 (8.13)	15.10 (5.95)
Apr	17.05 (6.71)	18.96 (7.47)	17.05 (6.71)	17.60 (6.93)	13.41 (5.28)	17.23 (6.78)	20.35 (8.01)	17.34 (6.83)
May	19.01 (7.49)	21.73 (8.55)	19.01 (7.49)	20.29 (7.99)	16.32 (6.43)	17.82 (7.02)	22.48 (8.85)	19.44 (7.65)
Jun	17.52 (6.90)	18.39 (7.24)	17.52 (6.90)	17.71 (6.97)	12.87 (5.07)	19.07 (7.51)	19.69 (7.75)	17.95 (7.07)
Jul	17.82 (7.02)	19.30 (7.60)	17.82 (7.02)	18.11 (7.13)	13.22 (5.21)	19.93 (7.85)	19.61 (7.72)	18.09 (7.12)
Aug	17.49 (6.88)	17.86 (7.03)	17.49 (6.88)	16.48 (6.49)	13.64 (5.37)	17.14 (6.75)	19.81 (7.80)	16.80 (6.61)
Sep	13.69 (5.39)	16.13 (6.35)	13.69 (5.39)	13.67 (5.38)	10.44 (4.11)	14.35 (5.65)	16.92 (6.66)	13.90 (5.47)
Oct	12.24 (4.82)	15.01 (5.91)	12.24 (4.82)	13.34 (5.25)	11.05 (4.35)	14.14 (5.57)	14.53 (5.72)	13.35 (5.25)
Nov	9.99 (3.93)	11.19 (4.41)	9.99 (3.93)	10.23 (4.03)	8.20 (3.23)	10.41 (4.10)	12.47 (4.91)	10.52 (4.14)
Dec	8.48 (3.34)	8.78 (3.46)	8.48 (3.34)	8.56 (3.37)	7.01 (2.76)	8.29 (3.27)	11.18 (4.40)	8.35 (3.29)
Year[‡]	--	183.8 (72.4)	153.6 (60.5)	172.4 (67.9)	133.9 (52.7)	174.6 (68.8)	205.7 (81.0)	170.4 (67.1)

[†] Indicates average values for all sites over five years, excluding missing data.

[‡] Indicates average sum over five years for each site, excluding missing data.

Table 3. Pan Coefficient (K_p) based on Evaporation Estimation with Equation 25 (1993 – 1997).

Month	Station							
	OK	HG	CL	BG	S5A	FT	S308	Average[†]
Jan	0.68	0.61	0.68	0.62	0.76	0.63	0.53	0.64
Feb	0.69	0.62	0.69	0.65	0.86	0.71	0.6	0.69
Mar	0.69	0.66	0.69	0.64	0.86	0.71	0.51	0.68
Apr	0.74	0.66	0.74	0.71	0.94	0.73	0.62	0.73
May	0.84	0.74	0.84	0.79	0.98	0.9	0.71	0.83
Jun	0.89	0.85	0.89	0.88	1.21	0.82	0.79	0.91
Jul	0.89	0.82	0.89	0.87	1.2	0.79	0.81	0.89
Aug	0.8	0.79	0.8	0.85	1.03	0.82	0.71	0.83
Sep	0.81	0.69	0.81	0.81	1.07	0.78	0.66	0.8
Oct	0.8	0.65	0.8	0.73	0.89	0.69	0.67	0.75
Nov	0.69	0.62	0.69	0.68	0.85	0.67	0.56	0.68
Dec	0.67	0.65	0.67	0.67	0.82	0.69	0.51	0.67
Average[‡]	0.77	0.7	0.77	0.74	0.95	0.74	0.64	0.76

[†] Indicates average over all sites for each month.

[‡] Indicates average for each site.

Energy Balance, Mass and Momentum Transfer

Physical approach of evaporation estimation accounts for the balance and transfer of energy, vapor and momentum. The vertical energy balance at the surface of water in the lake can be summed as the sum of heat fluxes between the air and water and E_o can be estimated as follows:

$$\lambda E_o = R_n - H - G \tag{2}$$

where λE_0 is latent heat flux; H is sensible heat (heat gained or lost by air at the surface); R_n is net radiation and G is heat gained or lost by upper layer of the lake. Net radiation is positive for energy flow to the surface, while the other terms are positive for energy flow away from the surface. λE_0 is negative during dew formation. Net radiation (R_n) is measured with net radiometers. In the absence of R_n data or when data quality is in question, the following equation can be used to estimate R_n from solar radiation (R_s) and net back or outgoing thermal radiation, R_b, (Jensen, 1974):

$$R_n = (1-\alpha) R_s - R_b \tag{3}$$

where α is short wave reflectance or albedo and R_b is estimated as follows:

$$R_b = \left[a \frac{R_s}{R_{so}} + b \right] R_{bo} \tag{4}$$

where a and b are coefficients (1,0) as recommended for humid areas (Jensen, 1974); R_{so} is mean solar radiation for a cloudless sky and R_{bo} is net outgoing thermal (long wave) radiation on a clear day and is estimated as follows (Jensen et al., 1990):

$$R_{bo} = \varepsilon' \sigma \frac{\left(T_{max}^4 + T_{min}^4\right)}{2} \tag{5}$$

where ε' is net emissivity; σ is Stefan-Bolzman constant (4.90x10^{-9} MJ m^{-2} K^{-4} day^{-1}); T_{max} and T_{min} are maximum and minimum daily air temperature at 2 m height in °K. Net emissivity is calculated as follows:

$$\varepsilon' = -0.02 + 0.261 \exp\left[-7.77\times10^{-4} T^2\right] \tag{6}$$

where T is mean air temperature (°C) at 2 m height.

Heat gained or lost by the upper layer of the lake (G) can be estimated from the following equation:

$$G = c_s d_w \left(T_n - T_{n-1}\right) \tag{7}$$

where c_s is water heat capacity; d_w is effective depth of water affected in change of heat storage for the given period; T_n is water temperature at end of period and T_{n-1} is water temperature at beginning of period. In the absence of lake water temperature measurements at the top layer, air temperature measurements at 2 m height can be substituted with an adjustment coefficient as shown for wetland case (Downey, 1998).

The general form of the equations expressing shear stress, latent heat and sensible heat fluxes are presented as follows.

$$\tau = \rho K_m \frac{du}{dz} \tag{8}$$

$$\lambda E_o = \frac{\lambda \varepsilon}{P} K_w \frac{de}{dz} \tag{9}$$

$$H = \rho c_p K_h \frac{dT}{dz} \tag{10}$$

where τ is shear stress; ρ is air density; K_m, K_w, and K_h are transfer coefficients for sheer stress, latent heat and sensible heat respectively; λ is the latent heat of vaporization of water; du/dz, de/dz and dT/dz represent the change in wind speed, vapor pressure and temperature with height, respectively; P is atmospheric pressure; ε is the ratio of molecular weights of water to dry air and c_p is specific heat of air.

The three transfer coefficients (K_m, K_w, and K_h) are dependent on wind speed, humidity, temperature, surface characteristics, and atmospheric stability. For most applications, it is commonly assumed that these three transfer coefficients are equal (Federer, 1970). Equations to estimate the heat transfer coefficient (K_h) has been expressed implicitly and explicitly. Explicit forms are presented as follows:

$$K_h \quad = \quad u_*^2 \frac{dz}{du} \qquad (11)$$

(Monteith, 1973), where u_* is friction velocity and dz/du is the inverse of the wind speed gradient.

$$K_h \quad = \quad \frac{k\, u_* \left(z - d + z_h\right)}{\phi_h} \qquad (12)$$

(Stannard, 1993), where k is the Von Karman constant (0.41); z is height; d is displacement height; z_h is roughness length for heat transfer; and ϕ_h is a stability corrector factor that is a function of the Monin-Obukhov length.

$$K_h \quad = \quad \frac{k\, u_*\, z}{\phi_h} \qquad (13)$$

$$K_h \quad = \quad u_* \theta_* \frac{dz}{dT} \qquad (14)$$

(Federer, 1970; Jacovides et al., 1992), where θ_* is temperature scale and is computed by equation (15) and dz/dT is the inverse of the temperature gradient.

$$\Theta_* \quad = \quad \frac{\Delta T\, k}{\ln\left(\frac{z_2}{z_1}\right)} \qquad (15)$$

where ΔT is temperature difference between the two levels of measurement (z_1 and z_2).

To directly apply the energy balance (Eq. 2), the estimation of H is difficult, as the determination of the transfer coefficient k_h and the temperature gradient is not easy. Penman in 1948 first derived the combination equation where energy required to cause evaporation and the mechanism required to remove vapor was considered (Jensen et al., 1990). Based on indoor and outdoor evaporation experiments, Penman developed the combination equation eliminating the need to evaluate vapor pressure and temperature right at the surface. The general form of the combination equation that was formulated to estimate evapotranspiration (ET) from a well watered grass is given as:

$$ET = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \gamma\, 6.43(a_w + b_w u_2)(e_a - e_d)}{\Delta + \gamma} \tag{16}$$

where ET is grass or alfalfa reference ET in mm d^{-1}; Δ is slope of vapor pressure curve (kPa °C^{-1}); γ is psychometric constant (kPa °C^{-1}); u_2 is wind speed at 2 m height in m s^{-1}; $(e_a - e_d)$ is vapor pressure deficit at 2 m height; and a_w and b_w are empirical wind coefficients. Equation 16 was calibrated to estimate ET from an open water marsh in a constructed wetland in South Florida (Abtew and Obeysekera, 1995). The following equations are the calibration results for the wind coefficients.

$$a_w = 0.10 + 3.0\exp\left[-\left(\frac{J - 173}{58}\right)^2\right] \tag{17}$$

$$b_w = 0.04 + 0.2\exp\left[-\left(\frac{J - 243}{80}\right)^2\right] \tag{18}$$

where J is the day of the year.

Stewart and Rouse (1976) studied evaporation for shallow lakes and ponds in the Hudson Bay lowlands and concluded that 55 percent of the net radiation is used for evaporation. The Priestley-Taylor model with an α value of 1.26 estimated daily shallow lakes evaporation with-in 5 percent of the value. The Priestley-Taylor model is a simplified form of the combination equation where the aerodynamic component is left out, but a coefficient that is greater than 1.0 is included as a multiplier.

$$ET = \frac{1}{\lambda}\alpha\left[\frac{\Delta}{\Delta + \gamma}\right](R_n - G) \tag{19}$$

Equation 19 was also applied to estimate ET from cattail marsh in South Florida, and the resulting calibration for α was 1.18 (Abtew and Obeysekera, 1995).

The mass-transfer models are based on the estimation of the net transport of water vapor from the water surface to atmosphere. By combining equation (9) and equation (8), the mass and momentum equations produce mass-transfer equation given as follows (Singh, 1989):

$$E_o = -\rho\, u_*^2 \frac{K_w (q_2 - q_1)}{K_m (u_2 - u_1)} \tag{20}$$

where, $(q_2 - q_1)$ is the difference in specific humidity at heights z_2 and z_1 above the water surface and $(u_2 - u_1)$ is the wind sheer between the same heights. Mainly theoretical based empirical mass-transfer equations have been developed based on simplified assumptions as adiabatic atmospheric condition and logarithmic wind profile. Hostetler and Bartlein (1990) applied a mass-transfer evaporation estimation model that was originally developed by Harbeck (1962) for modeling lake level variations of Harney-Malheur Lake in Oregon. E_o in mm is estimated as follows:

$$E_o = N u_2 (e_o - e_a) \tag{21}$$

N is an empirically determined mass-transfer coefficient (mm s m^{-1} kPa^{-1}); u_2 is wind speed at 2 m above lake surface (m s^{-1}); e_o is the saturation vapor pressure at the lake surface (kPa) and e_a is ambient vapor pressure of the air (kPa). The mass-transfer coefficient N for large surface area lakes is implicitly computed from lake surface area, A (km^2) as follows (Shuttleworth, 1993):

$$N = 2.909 A^{-0.05} \tag{22}$$

Other prospective methods of evapotranspiration estimation from lakes in subtropical humid areas are the radiation and temperature based methods. The simplest model that was used successfully to estimate marsh evapotranspiration in South Florida (Abtew, 1996a, 1996b) is given as follows:

$$ET = K_1 \frac{R_s}{\lambda} \tag{23}$$

where k_1 is a coefficient dependent on surface type; 0.53 for open water. In subtropical humid South Florida, most of the variation in evaporation is explained by the radiation than by the aerodynamic component of the evaporation models. Simple equations as equation 23, the Priestley-Taylor equation and similar equations can be adapted to remote (satellite based) regional ET estimation in South Florida. Temperature and radiation based models are simpler to monitor on surface or remote and have the potential to be used in tropical areas as South Florida. Equation 24 is a modified Turc (1961) model that requires only daily solar radiation and maximum temperature as indicators of evaporation (Abtew, 1996a).

$$E_o = \frac{k_2 (23.89 R_s + 50) T_{\max}}{(T_{\max} + 15)} \tag{24}$$

where E_o (mm d^{-1}), R_s (MJ m^{-2} d^{-1}), T_{max} is maximum daily temperature and k_2 is a coefficient. The original Turc equation, which has humidity component estimates k_2 as 0.013 for estimating ET in humid regions and average temperature, is used rather than maximum daily temperature. An equation based on solar radiation and maximum daily temperature was also applied to estimate marsh evapotranspiration in South Florida (Abtew, 1996a, 1996b).

$$E_o = \frac{1}{k_3} \frac{R_s T_{\max}}{\lambda} \tag{25}$$

where E (mm d^{-1}), R_s (MJ m^{-2} d^{-1}), T_{max} is maximum daily temperature, λ is latent heat of vaporization for water (MJ kg^{-1}) and k_3 is a coefficient (°C). A k_3 value of 52.6 °C was selected for estimating evaporation from Lake Okeechobee.

Water Budget

Water budget or mass balance is one of the methods often used to estimate evaporation from a lake. This method requires the measurement of inflows and outflows from the system, change in storage and estimation of evaporation as follows:

$$E_o = I - O + R + S_p - \Delta S + \varepsilon \qquad (26)$$

where I is inflow to the lake, O is outflow, R is rainfall, S_p is seepage, ΔS change in lake storage and ε is net error that is associated with measurement errors, estimation errors and errors associated with ungaged inflows and outflows. The water budget method will be applied on annual time steps to estimate E_o.

METEOROLOGY DATA

The climate of the region is sub-tropical characterized by tropical rainfall systems in the wet season and frontal rainfall in the dry season. About 63 percent of the annual rainfall occurs in the wet season (June through October) as reported in Sculley, 1985. Based on five years observation (1993 to 1997) from four weather stations on the lake, the mean annual air temperature is 23.4 ^{0}C (74 ^{0}F), and ranges from 15.9 ^{o}C (60.6 ^{0}F) in January to 30.9 ^{o}C (87.6 ^{0}F) in July. Generally it is a humid area with average daily humidity of about 79 %. There are four complete weather stations at different sites in Lake Okeechobee (Figure 1). Data is available as early as 1988 for station L005; since 1989 for station L006; since 1990 for LZ40 and since 1994 for station L001. Upon evaluation of the quality of solar radiation data in comparison with each other and five other land based weather stations, it was decided to use data from L006. It is assumed that better evaporation estimates can be computed using one quality data than averaging multiple stations with some questionable data. For this reason, the analysis period for all methods in this study is limited to the period 1993 to 1997.

Twenty seven rain gages around and inside lake Okeechobee were used to estimate average areal rainfall (Table 4). Based on available data from any number of stations, monthly and annual rainfall is summarized in Table 5. For five years of the study period, the average annual rainfall was 126.75 cm (49.9 inches) with standard deviation of 17.5 cm (6.9 inches). Average monthly meteorologic parameter data is presented in Table 6. Wind speed at 2-meter height is needed in equation 16 (Penman-Combination model) and equation 21 (mass-transfer model). Wind speed at 2-meter height was computed from wind speed measurements at 10 meter height inside the lake (station L006). The aerodynamic roughness (Z_o) estimation in the logarithmic wind profile equation requires roughness (wave) height estimation. Wave height (Z_w) was computed as follows (Linsley and Franzini, 1979):

$$Z_w = 0.5 V_w^{1.06} F^{0.47} \qquad (27)$$

where Z_w is the average wave height in cm, V_w is wind speed in km per hour and F is fetch or length of the water surface over which the wind blows in km. Daily calculated wave height is shown in Figure 2 and wind speed at 10 m and 2 m (height) is shown in Figure 3.

Daily meteorologic data over the lake is graphically depicted in Figure 4 (air and water temperatures); Figure 5 (maximum and minimum humidity) and Figure 6 (net and total solar radiation). Seasonal fluctuations of air temperature, water temperature and solar radiation clearly displayed seasonal characteristics and do correspond to variation in evaporation. This is a visual indication that temperature and radiation based equations can be applied to estimate evaporation in this region.

Table 4. Station Name, DBkey, and Period of Record (years) for Rainfall Stations in the Vicinity of Lake Okeechobee and on Lake Okeechobee.

Station Name	DBkeys	Period of Record
S133_R	05845	1970-1998
	16576	1991-1997
HGS6_R	06073	1938-1993
	06153	1948-1997
	06236	1942-1979
AHYC	16550	1993-1998
S135_R	05849	1971-1998
	16283	1995-1998
	16580	1991-1997
A308	15947	1993-1998
CANAL P2_R$^{\perp}$	06157	1953-1997
CANAL PT_R$^{\perp}$	16702	1994-1997
HGS5X_R	06123	1951-1993
	06242	1940-1991
	12747	1940-1991
PEL 23_R	05831	1974-1996
	05832	1963-1973
	16191	1995-1998
	06222	1929-1973
EAST SHO_R	05903	1963-1973
	05835	1970-1998
ABGL	16038	1993-1998
HGS4_R	06156	1951-1954
	06229	1951-1991
	06241	1942-1991
S2_R	05870	1973-1998
	16647	1991-1997
S3_R	06227	1967-1998
	07863	1988-1992
	16648	1991-1997
SFCD_R	05965	1980-1998

Station Name	DBkeys	Period of Record
S4_R	05879	1974-1998
	16650	1991-1997
HGS2_R†	06155	1948-1994
	06129	1951-1993
	06240	1940-1991
A310†	16551	1993-1997
S127_R	05911	1970-1998
	16284	1995-1998
	16573	1991-1997
L OKEE.M_R	05883	1976-1998
HGS1_R	06154	1918-1997
	06124	1951-1993
S129_R	05851	1978-1998
	16574	1991-1997
INDIANPM	15151	1990-1998
INDIAN P_R	05946	1968-1998
	06077	1956-1993
L001_R	16021	1994-1998
L005_R	12515	1988-1998
L006_R	12524	1989-1998
LZ40_R	13081	1990-1998
S131_R	06120	1965-1997
	15984	1993-1998
	16286	1995-1998
	16575	1991-1997
	F9544	1996-1997

$^{\perp}$ and † Indicates records were combined for these sites.

Table 5. Monthly and Annual Rainfall (cm) in and around Lake Okeechobee (1993-1997).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Sum
1993	16.99	6.05	10.77	4.52	8.86	12.22	9.42	12.7	15.7	12.6	4.42	1.88	116.13
1994	9.25	7.7	7.37	8	10.13	17.96	15.24	17.48	20.14	11.28	11.53	12.27	148.34
1995	6.27	5.54	8.99	6.15	7.75	18.34	20.27	21.59	16.13	25.91	2.03	1.24	140.21
1996	5.56	1.65	13.56	3.96	15.6	20.78	10.26	13.08	6.3	9.88	3.2	1.88	105.71
1997	3.43	2.74	5.89	14.58	12.5	16.36	13.69	15.37	14.55	2.54	9.8	11.53	122.99
Average	8.31	4.72	9.32	7.44	10.97	17.12	13.77	16.05	14.55	12.45	6.2	5.77	126.67
Standard Deviation	5.28	2.49	3	4.29	3.12	3.18	4.34	3.66	5.08	8.48	4.22	5.61	17.45
Minimum	3.43	1.65	5.89	3.96	7.75	12.22	9.42	12.7	6.3	2.54	2.03	1.24	105.71
Median	6.27	5.54	8.99	6.15	10.13	17.96	13.69	15.37	15.7	11.28	4.42	1.88	122.99
Maximum	16.99	7.7	13.56	14.58	15.6	20.78	20.27	21.59	20.14	25.91	11.53	12.27	148.34

Table 6. Average Daily Measured and Computed Weather Parameters at Station L006 on Lake Okeechobee.

Parameter	Units	Comment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature	C	average	18.09	18.62	20.37	22.84	25.53	27.09	27.88	27.67	27.26	25.35	21.79	18.4
Air temperature	C	maximum	20.67	21.75	23.39	25.57	28.49	30.22	30.9	30.6	29.77	27.65	24.13	21.05
Air temperature	C	minimum	15.86	15.95	17.96	20.68	23.45	24.86	25.75	25.58	25.46	23.65	19.86	16.13
Temperature	C	water, average	18.81	19.23	20.15	23.01	26.18	28.38	29.34	29.01	28.39	26.24	22.61	19.4
Temperature	C	water, maximum	19.84	20.42	21.42	24.37	28.27	30.64	31.36	30.79	29.63	27.16	23.51	20.28
Temperature	C	water, minimum	18.09	18.35	19.22	22.11	25.03	27.44	28.51	28.35	27.85	25.72	21.99	18.68
Air pressure	kPa	average	101.89	101.84	101.79	101.72	101.68	101.66	101.83	101.71	101.51	101.48	101.68	101.83
Rel. humidity	%	minimum	68.94	66.39	63.78	61.56	61.16	64.25	63.96	65.96	68	69.63	71.78	71.53
Rel. humidity	%	maximum	92.92	94.49	92.74	89.96	90.9	92.48	90.94	91.63	91.18	91.97	92.93	94.91
Net solar Rad[†]	MJ m-2d-1	average	8.71	11.63	14.82	17.12	16.89	16.01	15.12	12.13	10.39	8.64	6.62	6.03
Total solar Rad.	MJ m-2d-1	average	11.54	14.79	18.71	21.01	23.22	21.86	20.99	18.81	15.8	15.05	12.32	11.2
Wind speed[‡]	m	2 m	3.48	3.63	3.92	3.91	3.39	3.09	2.8	2.88	2.96	3.53	3.82	3.53
Wind speed	m	10 m	5.02	5.29	5.76	5.68	4.84	4.36	3.91	4.04	4.16	5.08	5.59	5.12
Wave height[⊥]	cm	average	47.59	50.32	55.1	54.22	45.74	40.89	36.5	37.82	38.94	48.15	53.41	48.66
Simple	mm/d	evaporation	2.49	3.19	4.04	4.55	5.05	4.76	4.61	4.1	3.44	3.27	2.67	2.42
Turc	mm/d	evaporation	2.3	2.92	3.71	4.27	4.88	4.71	4.6	4.13	3.5	3.27	2.61	2.27
Rt-Tmax	mm/d	evaporation	1.84	2.5	3.41	4.18	5.18	5.2	5.13	4.54	3.7	3.26	2.31	1.84

[†] Computed based on equations 3,4,5, and 6.

[‡] Calculated from measured wind speed at 10 m height, fetch distance, and wave height.

[⊥] Calculated from fetch distance and wind speed measured at 10 m height.

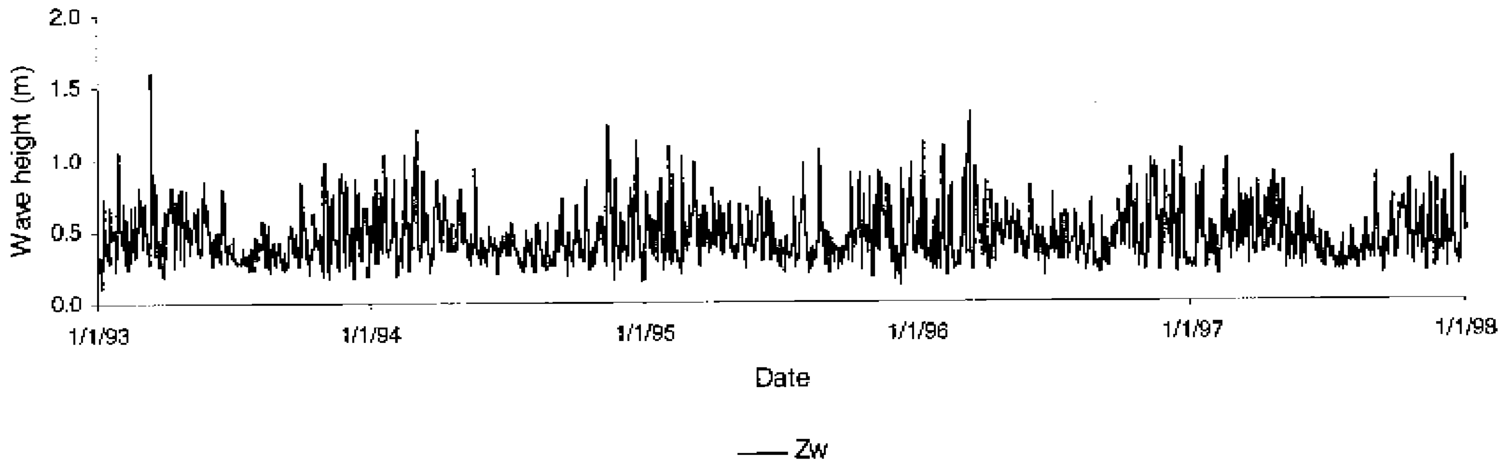

Figure 2. Daily Wave Height (Z_w) Calculated at Station L006.

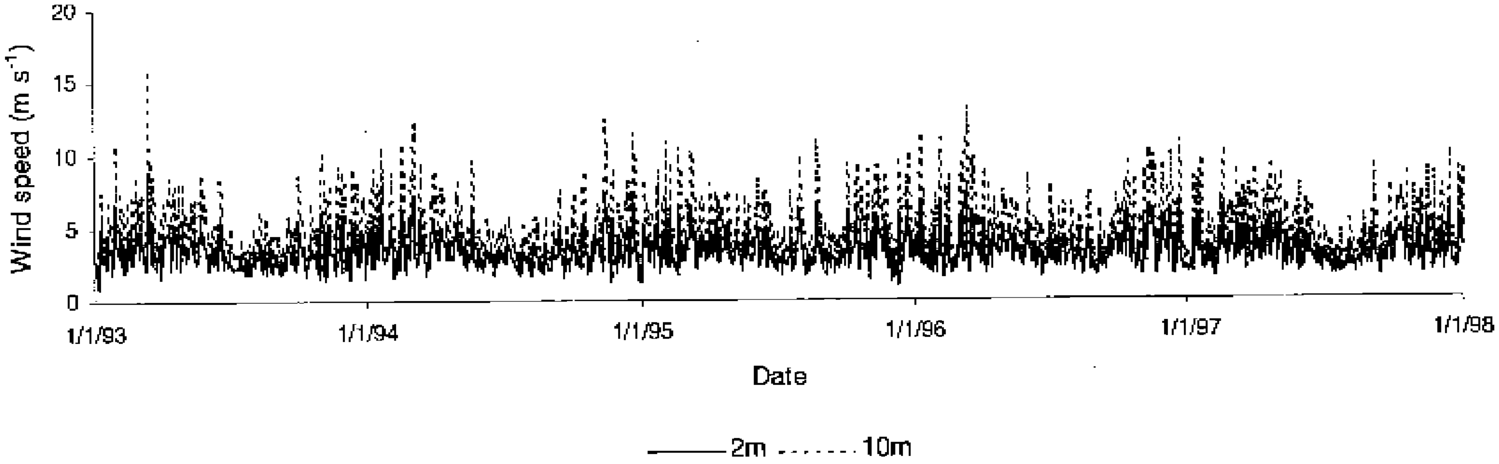

Figure 3. Daily Average Wind Speed Measured at 10 m Height and Calculated for 2 m Height at Station L006.

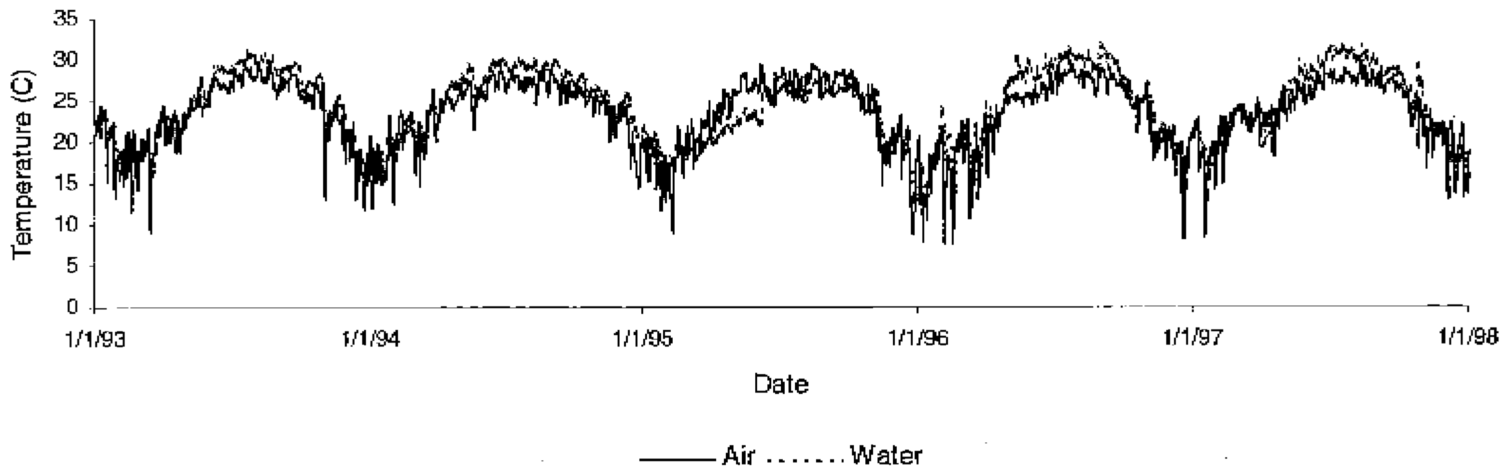

Figure 4. Daily Average Water and Air Temperatures at Station L006.

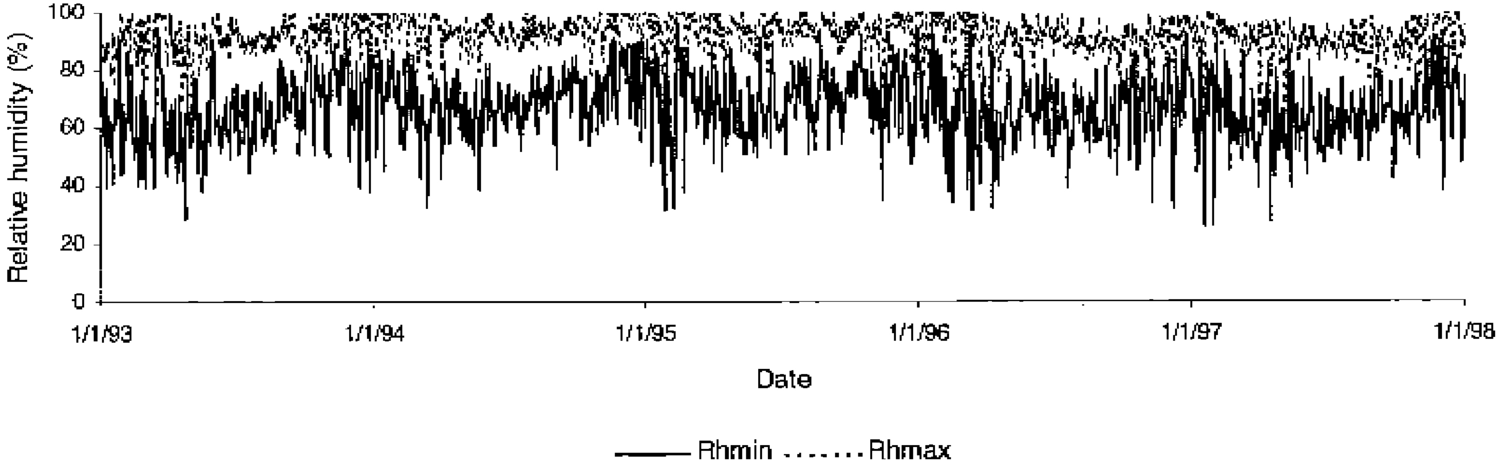

Figure 5. Daily Minimum and Maximum Relative Humidity at Station L006.

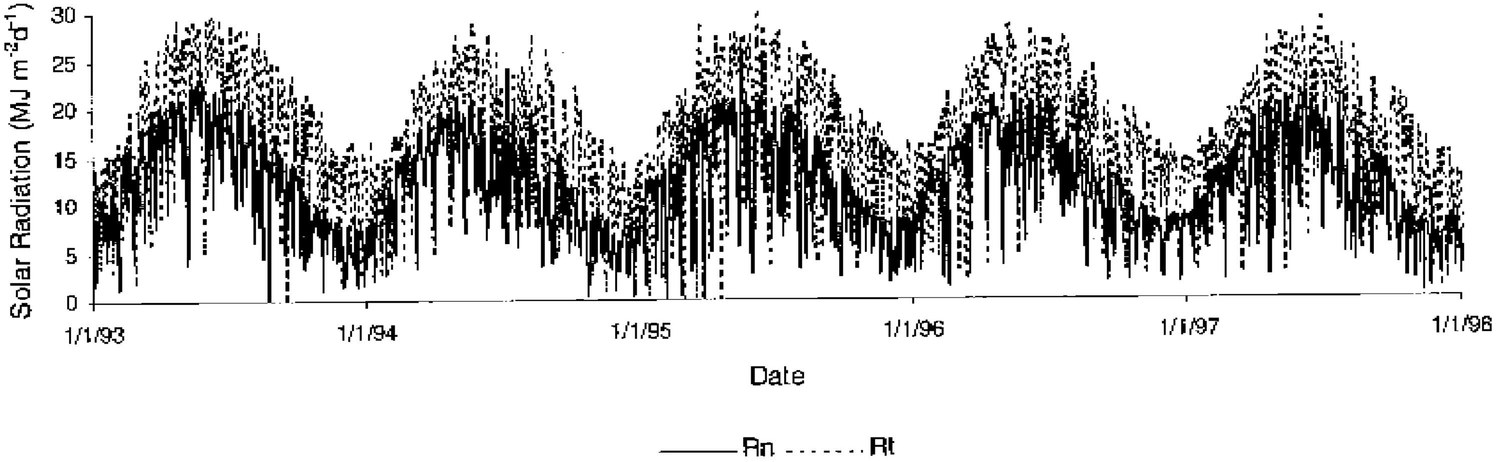

Figure 6. Daily Average Total Solar Radiation (R_t) and Computed Net Radiation (R_n) at Station L006.

MODEL APPLICATION

Daily meteorologic data was used in the application of six models to estimate evaporation from Lake Okeechobee. The water budget model was applied as the seventh method for estimating Lake Okeechobee evaporation. Comparison of results showed that the Penman-Combination model (equations16,17,18) and the Priestley-Taylor model consistently overestimated evaporation compared to the other models and literature values. These two models also require the most number of parameters. The mass transfer coefficient, N, in equation (21), is suggested to be determined for every reservoir (Harbeck, 1962). The mass-transfer model (equ. 21) seems to have low adaptability to tropical lakes and reservoirs evaporation estimation. Various attempts to adjust N did not provide acceptable estimates of E_0 for Lake Okeechobee, and the seasonal variation of evaporation was not maintained. In this region where generally humidity and frequency of rainfall are high and solar radiation is the main variable in evaporation estimation, wind speed and vapor pressure deficit based models may not perform well.

The simple equation (equ. 23), modified Turc (equ. 24) and the solar radiation-maximum temperature equation (equ. 25) provide relatively close and expected estimates of lake evaporation with minimum of measured or estimated parameters needed. With the postulation that maximum air temperature and solar radiation explains most of the variability in evaporation in South Florida (Abtew, 1996a), equations 23, 24 or 25 can be used to estimate Lake Okeechobee daily evaporation (Figure 7a, 7b, 7c). The average estimates of the three methods was 132 cm (52 inches) for the five year study period. Annual evaporation estimation using the water budget model is shown in Table 7. In equation (26), Seepage (S_p) and errors (ε) are assumed to be zero. The water budget estimate is about 10% higher than the other methods (Table 8). Seepage losses from the lake and other errors may be a factor in the higher evaporation estimation with the water budget method.

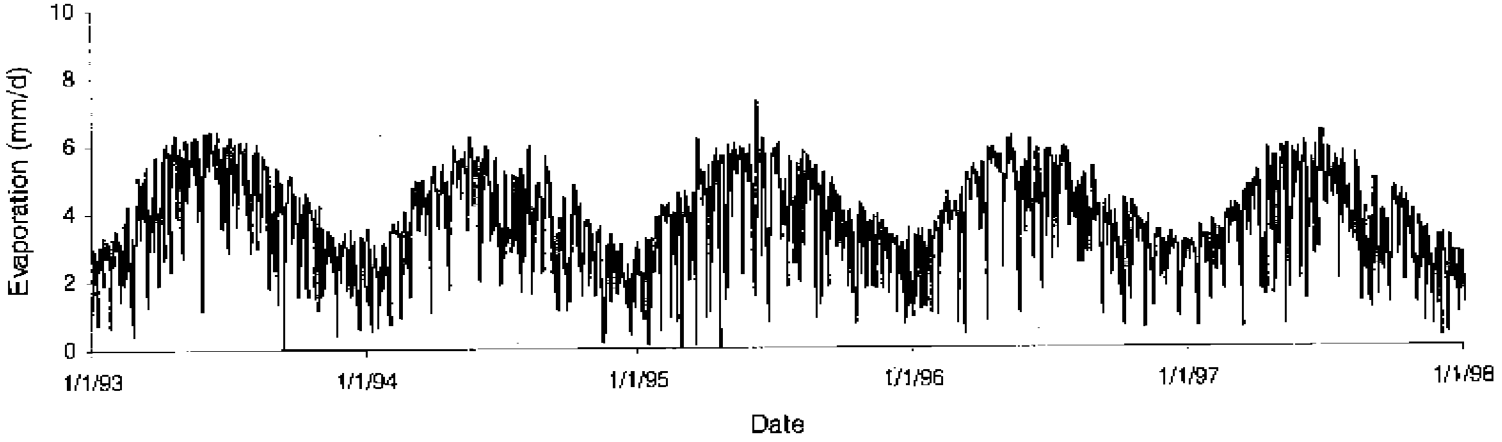

Figure 7a. Daily Evaporation Estimations at Station L006 for Simple Model (Equation 23).

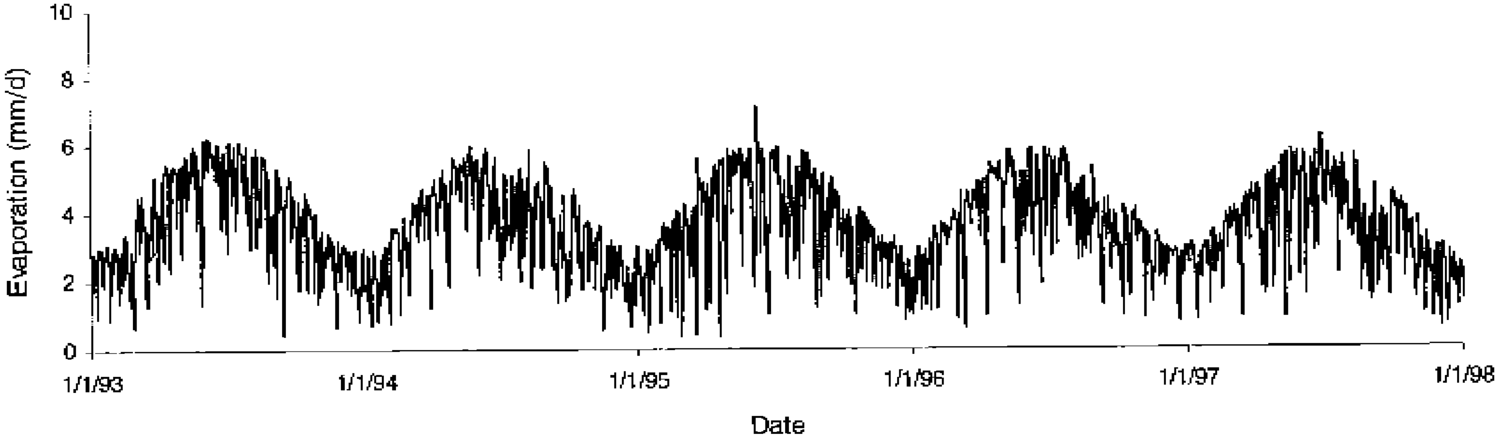

Figure 7b. Daily Evaporation Estimations at Station L006 for Modified Turc Model (Equation 24).

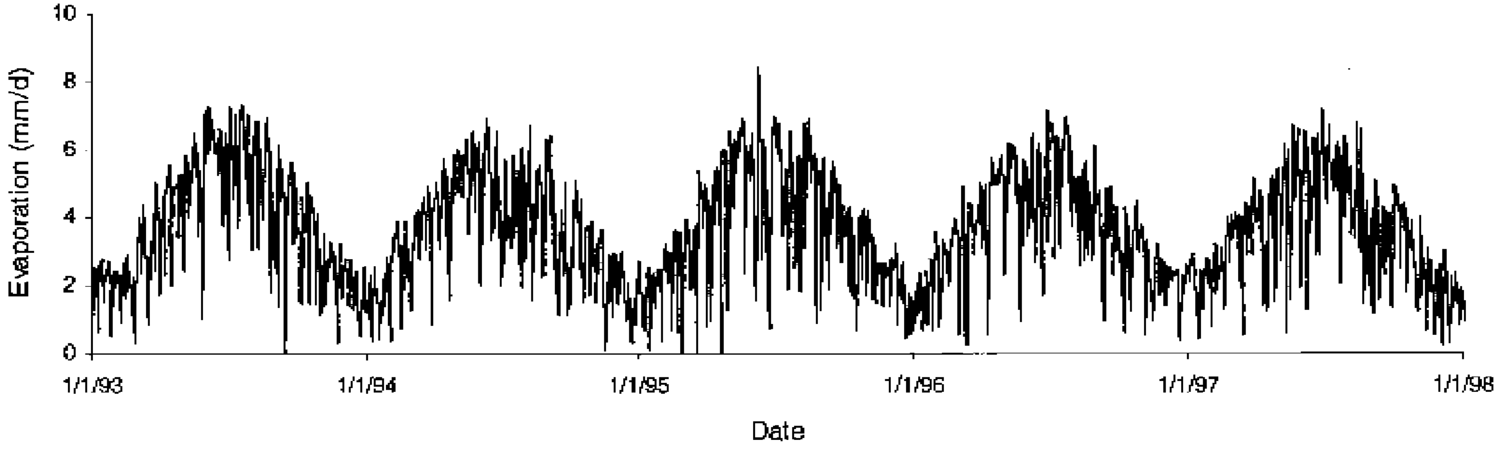

Figure 7c. Daily Evaporation Estimations at Station L006 for Rt-Tmax Model (Equation 25).

Table 7. Lake Okeechobee Water Budget Method Evaporation Estimates (1993 – 1997).

Year	Inflow	Outflow	End Stg[†]	Avg. Stg[‡]	Ch.Stor[⊥]	Area[+]	Ch.Stor[⊥]	Inflow	Outflow	Rain	Ch. Stor[⊥]	Evap[*]
	ha-m	ha-m	m	m	cm	ha	ha-m	cm	cm	cm	cm	cm
1993	189254	239989	4.29	4.57	-55.49	181457	-100622	104.3	132.3	116.1	-55.5	143.6
1994	375626	207350	5.32	4.81	103.35	182958	188973	205.4	113.4	148.4	103.3	137
1995	417571	487293	4.96	5.14	-36.28	184269	-66811	226.7	264.5	140.2	-36.3	138.6
1996	151117	181226	4.28	4.62	-67.68	181717	-122912	83.2	99.8	105.7	-67.7	156.8
1997	273804	80242	5.13	4.71	84.45	182130	153712	150.4	44.1	123	84.4	144.9

[†] Year end water level in Lake Okeechobee (4.8 m for 1992).

[‡] Average stage for year used to compute area.

[⊥] Change in lake storage.

[+] Lake area computed from stage-area information.

[*] Lake evaporation computed from water budget.

Table 8. Annual Lake Okeechobee Evaporation (cm) Estimation Using Four Methods.

Year	Simple[†]	Turc[‡]	Rt-Tmax[⊥]	Water Budget[']
1993	142	137	137	144
1994	128	126	126	137
1995	136	132	132	139
1996	140	134	132	157
1997	131	128	127	145
Average	135	131	131	144

[†] Equation 23.

[‡] Equation 24.

[⊥] Equation 25.

['] Equation 26 (assuming seepage and errors of zero).

CONCLUSION

Seven methods of evaporation estimation from Lake Okeechobee were evaluated using site measured data. Simple models based on solar radiation and maximum air temperature can be used to estimate daily evaporation from Lake Okeechobee. Lake evaporation estimates can be reported the next day based on automated calculations at the lake weather station site or at headquarters. Equations (25), (24) or (23) can be used based on available data and have applicability to remote sensing. Although the pan method can provide estimates of evaporation in the absence of alternatives, it has certain limitations. The pan coefficient is dependent on time of the year and the specific pan station in use. In this study, monthly and annual pan coefficient estimates for seven pan stations in the vicinity of Lake Okeechobee are provided.

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