COMPARISON OF METHODS USED TO ESTIMATE LAKE EVAPORATION FOR A WATER BUDGET OF LAKE SEMINOLE, SOUTHWESTERN GEORGIA AND NORTHWESTERN FLORIDA

Melinda S. Mosner and Brent T. Aulenbach

AUTHORS: Hydrologists, U.S. Geological Survey, 3039 Amwiler Road, Suite 130, Peachtree Business Center, Atlanta, Georgia 30360-2824.
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Abstract. Four empirical methods for calculating evaporation were compared with calculations of evaporation using the energy budget for Lake Seminole, southwestern Georgia and northwestern Florida, for April 2000–September 2001. Methods compared were the Priestly-Taylor, Penman, DeBruin-Keijman, and Papadakis equations. Evaporation calculated using the energy budget and empirical methods then were compared with estimates published daily by the Georgia Automated Environmental Monitoring Network (GAEMN) (2002). Average monthly lake evaporation using the energy budget method was 5.6 inches. Monthly estimates of evaporation from the GAEMN were 20 percent lower, and similar estimates derived from the empirical equations were as much as 16 percent higher, than evaporation estimated using the energy budget. Despite these large discrepancies between evaporation estimates, the effect on the lake water budget is small, because evaporation accounts for only about 1 percent of total lake outflow.

INTRODUCTION

Lake Seminole, impounded during the late 1940s to mid-1950s with the construction of Jim Woodruff Lock and Dam on the Apalachicola River, is a 37,600-acre lake located in the lower Apalachicola-Chattahoochee-Flint (ACF) River Basin at the boundary between southwestern Georgia and northwestern Florida (Fig. 1). Despite its size, Lake Seminole is essentially a run-of-the-river impoundment, having less than 67,000 acre-feet of storage. About 240 miles of shoreline are distributed around four impoundment arms: two major arms extend the lake from the dam about 47 miles upstream along the natural courses of the Chattahoochee and Flint Rivers; and two minor impoundment arms are created along Fishpond Drain and Spring Creek, both of which are tributaries to the Flint River arm of the lake (U.S. Army Corps of Engineers, 1980).

Recently, Lake Seminole and the water released from it have become a focal point in water-allocation negotiations between Georgia, Florida, and Alabama, which resulted from the ACF River Basin Compact. Increases in population, agriculture, and industry have made water supply and use in the lower ACF River Basin a major concern for water managers in the region as the three states compete for the basin's limited water resources. These concerns led the three states to sign an interstate water compact in 1997, which is intended to ensure the equitable use and availability of the water resources in the region, while protecting river ecology. Essential to the State of Georgia's water-allocation plans was the necessity to undertake a technical study to develop a comprehensive water budget of the Lake Seminole area (Harold F. Reheis, Director, Georgia Department of Natural Resources, Environmental Protection Division, written commun. with Lynn Torak, USGS, 1997).

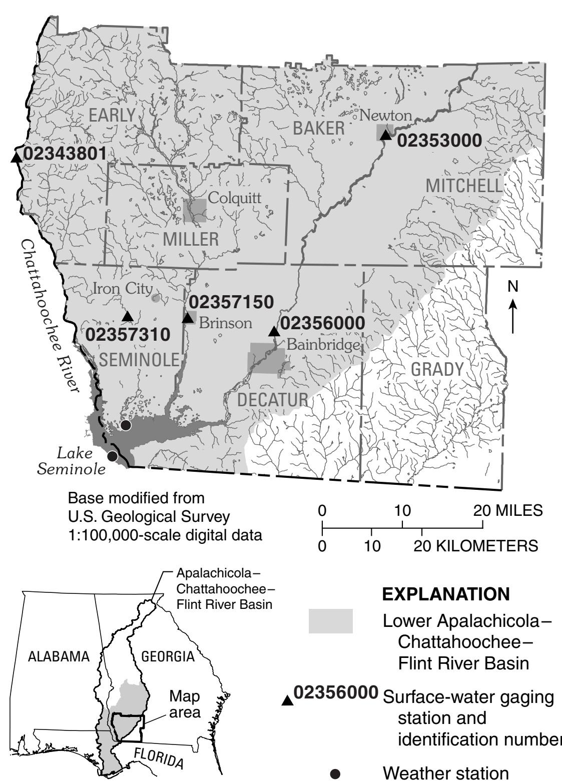

Figure 1. Study area and surface-water gaging and weather stations in area surrounding Lake Seminole.

Data Collection Methods

Climatological data needed to estimate lake evaporation were collected from two overwater meteorological stations operated by the GAEMN. Lake temperature, precipitation, wind speed and direction, air temperature, and net radiation measurements were recorded every 15 minutes and summarized on a daily basis at each station. In addition to these stations, Lake Seminole's size and irregular geometry required that detailed thermal surveys be conducted to measure accurately the heat content of the lake. Lake temperature data were collected from 100 temperature probes arranged at various depths at 26 locations throughout the lake, providing data necessary to calculate average lake temperature by the energy-budget method and the Priestly-Taylor, Penman, and DeBruin-Keijman equations.

Evaporation Calculations

Lake evaporation was calculated using the energy budget method as well as using four empirical equations: the Priestly-Taylor, Penman, DeBruin-Keijman, and Papadakis equations (Winter and others, 1995). These estimates were compared to each other and then to results published daily by the GAEMN (2002), which uses the Priestly-Taylor equation. Differences in results between the two Priestly-Taylor estimates arise from the manner in which lake-temperature measurements are used to determine heat stored in the lake—the GAEMN uses lake temperature measured at the meteorological stations only; whereas, the Priestly-Taylor calculation employs a more detailed heat budget, using temperature measurements collected from the temperature-probe network located throughout the lake.

Energy Budget. The energy budget (Lee and Swancar, 1996) (eq. 1) is recognized as the most accurate method for determining lake evaporation (Rosenberry and others, 1993). It is also the most costly and time-consuming method, requiring estimates of heat added to the lake from net radiation, surface water, ground water, and direct precipitation; heat lost by the lake from surface water and ground water; and change in heat stored in the lake. The net addition of heat to the lake that does not result in an increase in lake heat storage is then attributed to evaporation. The evaporation rate, E_{EB}, is given by

$$E_{EB} = \frac{Q_s - Q_r + Q_a + Q_{ar} - Q_{bs} + Q_v - Q_x}{L\,(1 + BR) + T_0}\,, \quad \text{(cm/day)} \qquad (1)$$

where

E_{EB} = evaporation, in centimeters per day (cm/day);
Q_s = incident shortwave radiation, in calories per square centimeter per day (cal/cm^2/day);
Q_r = reflected shortwave radiation (cal/cm^2/day);
Q_a = incident longwave radiation from atmosphere (cal/cm^2/day);
Q_{ar} = reflected longwave radiation (cal/cm^2/day);
Q_{bs} = longwave radiation emitted by lake (cal/cm^2/day);
Q_v = net energy advected by streamflow, ground water, and precipitation (cal/cm^2/day);
Q_x = change in heat stored in water body (cal/cm^2/day);
L = latent heat of vaporization, in calories per gram (cal/g);
BR = Bowen Ratio, dimensionless; and
T_0 = water-surface temperature (ºC).

Average monthly estimates of evaporation using the energy budget range from 2.4 to 7.1 inches (Fig. 2), averaging 5.6 inches (Table 1) for the study period.

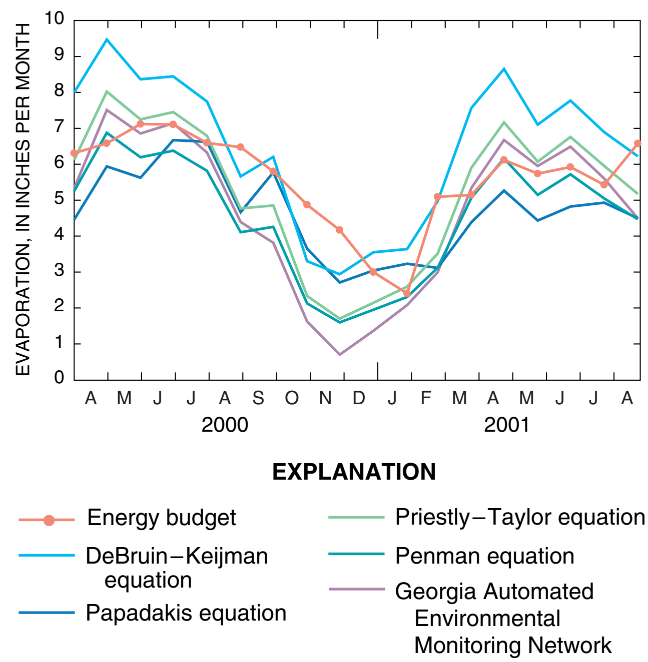

Figure 2. Comparison of monthly estimates of evaporation using empirical equations and the energy budget.

Priestly-Taylor Equation. The Priestly-Taylor equation (Winter and others, 1995) calculates potential evapotranspiration (PET) or evaporation as a function of latent heat of vaporization and heat flux in a water body, and is defined by the equation

$$PET = \alpha(s/s + \gamma))[(Q_n - Q_x)/L], \quad \text{(cm/day)} \qquad (2)$$

where terms in eq. 2 not defined previously are

α = 1.26, Priestly-Taylor empirically derived constant, dimensionless;
$(s/s + \gamma)$ = parameters derived from slope of saturated vapor pressure-temperature curve at the mean air temperature; γ is the psychrometric constant, s is the slope of the saturated vapor pressure gradient, dimensionless; and
Q_n = net radiation ($cal/cm^2/day$).

Monthly estimates of evaporation using the Priestly-Taylor equation range from 1.7 to 8.0 inches (Fig. 2), averaging 5.3 inches (Table 1) for the study period. The Priestly-Taylor equation most closely agrees with the energy budget method; monthly differences range from an underestimation of 2.5 inches for December 2000, to an overestimation of 1.4 inches for April 2000 (Fig. 2), averaging an underestimation of 0.3 inches for the study period. The total difference in evaporation estimation between the Priestly-Taylor equation and the energy budget was -5.9 inches (Table 1).

Table 1. Comparison of evaporation rates determined using empirical equations to evaporation rates determined using the energy budget method

[GAEMN, Georgia Automated Environmental Monitoring Network; n/a, not applicable]

	DeBruin-Keijman	Pen-man	Priestly-Taylor	Papa-dakis	GAEMN	Energy Budget
Monthly minimum	2.9	1.6	1.7	2.7	0.7	2.4
Monthly maximum	9.5	6.9	8	6.7	7.5	7.1
Monthly average	6.5	4.5	5.3	4.7	4.7	5.6
Monthly median (inches)	7	5.1	5.9	4.6	5.3	5.9
Total evaporation (inches) Apr 2000–Sept 2001	116.5	81.6	94.6	83.8	84.7	100.4
Total difference empirical equation minus energy budget (inches)	16.1	-18.9	-5.9	-16.6	-15.8	n/a
Annual evaporation (inches/ year) Apr 2000–Mar 2001	77.7	54.4	63	55.9	56.5	67

Penman Equation. The Penman equation (Winter and others, 1995) calculates evaporation based on the energy that is removed from the water-body surface to create water vapor and is defined by the equation

$$PET = (s/s + \gamma))(Q_n - Q_x) + (\gamma/(s + \gamma))[(15.36(0.5 + 0.01U_2))*(e_0 - e_a)], \quad \text{(cm/day)} \qquad (3)$$

where new terms in eq. 3 are defined as

$\gamma/(s + \gamma)$ = derived from slope of saturated vapor pressure-temperature curve at the mean air temperature; γ is the psychrometric constant, s is the slope of the saturated vapor pressure gradient, dimensionless;
U_2 = wind speed at 2 m height, in meters per second (m/s);
e_0 = saturated vapor pressure, in millibars (mbars); and
e_a = vapor pressure at temperature and relative humidity of the air (mbars).

Monthly estimates of evaporation using the Penman equation range from 1.6 to 6.9 inches (Fig. 2), averaging 4.5 inches (Table 1) for the study period. Differences in evaporation estimations, when compared with the energy budget method, range from an underestimation of 2.7 inches in December 2000, to an overestimation of 0.3 inches in April 2001, underestimating by an average of 1.1 inches for the study period. The accumulated error between the Penman equation and the energy budget was the highest of all the empirical equations, -18.9 inches (Table 1).

DeBruin-Keijman Equation. The DeBruin-Keijman equation (Winter and others, 1995) determines evaporation rates as a function of the moisture content of the air above the water body, the heat stored in the lake, and the psychrometric constant, which is a function of atmospheric pressure and latent heat of vaporization.

$$PET = [SVP/0.95SVP + 0.63\gamma)]*(Q_n - Q_x), \quad \text{(cm/day)} \quad (4)$$

where, SVP is saturated vapor pressure at mean air temperature, in millibars per degree Kelvin (mbars/K), and all other terms have been defined previously.

Monthly estimates of evaporation using the DeBruin-Keijman equation ranged from 2.9 to 9.5 inches (Table 1). When compared with the energy budget, the DeBruin-Keijman equation underestimated evaporation by as much as 1.6 inches and overestimated evaporation by as much as 2.9 inches (Fig. 2). During the study period, the total difference in evaporation estimation between the DeBruin-Keijman equation and the energy budget was 16.1 inches (Table 1).

Papadakis Equation. The Papadakis equation (Winter and others, 1995) does not account for the heat flux that occurs in the lake body to determine evaporation. Instead, the equation depends on the difference in the saturated vapor pressure above the water body at maximum and minimum air temperatures, and evaporation is defined by the equation

$$PET = 0.5625[e_0max - (e_0min\text{-}2)], \qquad (cm/day) \qquad (5)$$

where all terms have been defined previously.

Monthly estimates of evaporation using the Papadakis equation ranged from 2.7 to 6.7 inches (Table 1). In comparison with the energy budget method, the Papadakis equation underestimated evaporation by as much as 2.1 inches and overestimated by 0.8 inches (Fig. 2). During the study period, the total difference in evaporation estimation between the Papadakis equation and the energy budget was -16.6 inches (Table 1).

DISCUSSION

Compared to the energy budget, the Priestly-Taylor method best estimated evaporation, followed by the GAEMN, DeBruin-Keijman, Papadakis, and Penman equations. Evaporation estimates calculated using the Priestly-Taylor equation differ from those calculated using the energy budget by about 4 inches annually (Table 1), a difference of about 6 percent (Table 2).

Table 2. Comparison of empirical equations to the energy budget for determining evaporation from Lake Seminole

[%, percent; Priestly-Taylor equation calculated by the Georgia Automated Environmental Monitoring Network (GAEMN). (Accessed Nov. 19, 2002 at URL: http://www.griffin.peachnet.edu/bae.)]

	Percent difference in evaporation from energy budget				
Month	**DeBruin-Keijman**	**Pen-man**	**Priestly-Taylor**	**Papa-dakis**	**GAEMN**
Apr 2000	26.8	-16.7	-3	-29.3	-15.4
May 2000	43.8	4.4	21.9	-9.8	14.1
June 2000	17.6	-13	1.9	-21	-3.7
July 2000	18.8	-10.3	4.8	-6.1	0.5
Aug 2000	17.5	-11.8	3	0.5	-4.1
Sept 2000	-12.6	-36.6	-26.3	-27.9	-32.2
Oct 2000	7	-26.6	-16.4	-0.4	-34.2
Nov 2000	-32.2	-56.3	-52.1	-25	-66.7
Dec 2000	-29.5	-61.7	-59.2	-35	-83.2
Jan 2001	18.6	-34.8	-28.5	1.6	-54.4
Feb 2001	51.3	-4.1	7.8	34.3	-13.6
Mar 2001	-2.4	-38.7	-31	-38.8	-41.2
Apr 2001	47.1	-1.5	14.7	-14.7	3.8
May 2001	41.4	0.7	17.1	-14	9.1
June 2001	23.7	-10.3	5.8	-22.8	3.7
July 2001	31.2	-3.5	14.1	-18.6	9.6
Aug 2001	27.1	-7	9.7	-9.1	3.3
Sept 2001	-5.4	-32.1	-21.4	-31.6	-31.7
Average %	**16.1**	**-20**	**-7.6**	**-14.9**	**18.7**

GAEMN evaporation estimates differ from the energy budget by about 16 inches annually, about a 19-percent difference. However, use of the GAEMN estimate, which has a higher error than the energy budget or Priestly-Taylor methods, may be acceptable for the purpose of understanding the Lake Seminole water budget. Because evaporation accounts for about 1 per cent of the water budget for Lake Seminole, using the GAEMN to calculate evaporation amounts to a normalized discrepancy of only 0.2 to 2.6 percent of outflows in the water budget (Table 3). This relatively small error, when compared to the magnitude of other components of the water budget, make using the existing estimates from the GAEMN reasonable for the purposes of the Lake Seminole water budget. This simpler method eliminates the need to collect labor-intensive lake temperature profiles for the energy budget and continuous development and calculation of the water budget of Lake Seminole.

Table 3. Normalized percent discrepancy of outflow for Lake Seminole water budget attributed to evaporation

				2000				
Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1.1	2.6	2	2.4	2	1.5	2.4	2.3	1.6
				2001				
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
0.8	0.7	0.2	0.4	1.6	0.6	1.1	1.1	1.3

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